



**Architectural Experience and Motion:  
a design tool based on simulation and immersing technologies**

by  
Razvan Neagu  
Institutul de arhitectura "Ion Mincu"  
1988

Submitted to the Department of Architecture  
in Partial Fulfillment of the Requirements for the degree of  
**MASTER OF ARCHITECTURE**  
at the  
**MASSACHUSETTS INSTITUTE OF TECHNOLOGY**  
May 1993

© Razvan Neagu, 1993. All rights reserved.

The author hereby grants to MIT permission to reproduce and to distribute  
publicly copies of this thesis document in whole or in part.

Signature of the author

Razvan Neagu, Department of Architecture  
May 7, 1993

Certified by

William J. Mitchell  
Dean of the School of Architecture and Planning  
Thesis Supervisor

Accepted by

Rotch

Roy J. Strickland  
Chairman, Departmental Committee on Graduate Students

MASSACHUSETTS INSTITUTE  
OF TECHNOLOGY

MAY 02 1993

LIBRARIES



**Architectural Experience and Motion:  
a design tool based on simulation and immersing technologies**

by

Razvan Neagu

Submitted to the Department of Architecture on May 7, 1993  
in partial fulfillment of the requirements for the degree of  
MASTER OF ARCHITECTURE

**ABSTRACT**

**Visualization** is an important aspect of architectural design. This field has evolved and influenced continuously the design medium and process. Architecture implies experience of space and experience relies on motion. Presently, the visualization process offers minimal experiential feed-back as it lacks immersive and proprioceptive output.

Recent technological leaps necessitate a re-evaluation of the architectural visualization process. Advancements in flight simulation and virtual reality applications can be implemented in new tools for architects. This thesis defines the parameters of a 3D, immersive design tool. The proposed tool provides feed-back beyond photo-realism, tapping into the experiential qualities of the designed spaces.

The parameters of the proposed tool extend the boundaries of architectural visualization into **experientialization**. These alternatives investigate the use in architecture of digital 3D environments and space/time continuum. Modeling, manipulation, and navigation are analyzed and concrete original implementations are shown. A new method, similar to a **3D parallel ruler**, is demonstrated to overcome constraints in representation, imposed by two-dimensional displays.

Immersion and engagement are necessary for the simulation of a compelling architectural experience. An analysis of stimuli and determination of necessary levels of input is performed. For this, it is important to understand perception and environmental properties. In this thesis, a phenomenological approach to architectural experience analysis is employed.

The practical application of the proposed tool is critical. Specific hardware and software analysis is performed to assure the feasibility of implementing such a tool.

Thesis Supervisor: William J. Mitchell  
Title: Dean of the School of Architecture and Planning





*This thesis is dedicated to my sister, **Adriana**, her husband, **Eugen**, and my godparents, **Sanda** and **Liviu**. Without their concern, love and financial support I would not have been able to be part of the MIT community.*

### **Acknowledgments**

I would like to thank very much **Bill Mitchell** for taking the time to be my thesis advisor. His insight illuminated so well the path that I have pursued.

Many thanks, from the bottom of my heart, to **Douglas Trumbull** and **Anne Vidor**, for their generosity and hospitality. Without their support and practical vision this thesis would have not been possible.

I would like to thank **Glorianna Davenport** for her help in keeping me focused on the scope and goals of this thesis.

Thanks to **Rosemary Grimshaw** for her insights on the complex notion of architectural experience.

I would like to thank my parents, **Luci** and **Romica** for all their love and support since I have left Romania and for knowing that they were always, in spirit, there for me.

Greatest appreciation for **Marnie**, her love, friendship, spirit, and long hours of work with me. She made the impossible possible.





















Many thanks to **Zsuzsanna** for her friendship and support. I am grateful for her advice and intense help during the last burning days and nights.

I would like to thank everybody from **The Trumbull Company**, **Silicon Graphics Inc.** and **Software Systems**, for their support and competent technical advice.

Last, but not least, I would like to thank my servile companionships, **HAL** - a PC compatible Austin 486/33i, and **Iris** - a Silicon Graphics Indigo Elan 4000, for being there, 24 hours a day and seldom crashing...



## TABLE OF CONTENTS

1.  Overview .....	9
2.  Existing conditions .....	15
3.  Proposal .....	21
3.1.  Input .....	21
3.2.  Output.....	25
3.3.  Libraries of objects .....	30
3.4.  Experiential storytelling .....	31
3.4.1.  Immersion .....	34
4.  Experience of space.....	39
4.1.  Perception .....	39
4.1.1.  Phenomenal approach to perception.....	41
4.1.2.  Phenomenal approach to architecture.....	43
4.1.3.  Form.....	46
4.1.4.  Motion.....	49
4.2.  Interpretation .....	53
5.  Software structure .....	57
5.1.  Modeling.....	57
5.2.  Positioning.....	77
6.  Bibliography .....	97
7.  Photo Credits.....	105



## 1. Overview

With visual information advancements in this video age, our society depends more and more upon the enticing world of images. This tendency is particularly insufficient in the architectural design process. A static 2D image provides valuable information on a series of architectural aspects, but gives little feed-back on the most important: the **experience** of built space. Recent developments in such high-tech fields as virtual reality and flight simulation are opening the doors to a better understanding of the experiential qualities of designed environments. One can propose an integrated use of existing technologies which would maximize relevant information in the design process. This thesis defines the parameters for a **spatial design tool** which would enable the architect to sketch beyond form. This tool proposes a method of understanding architecture on multiple levels by helping the designer to tap into the **experiential** qualities of three dimensional space.

### Existing conditions and proposal

This thesis analyzes the existing working media and methods used in the architectural design process. A cursory assessment shows that the tools,

presently provided to architects, do not provide information as complete as the technology of the modern age can offer. The inputs and displays are two-dimensional and mostly static. Architecture, however, is highly experiential, though. There is no architecture without experience. The tools used by architects now provide little of the useful experiential information. The proposed design system challenges the boundary of traditional architectural feedback. This thesis proposes to enhance the designers ability to pre-visualize architectural space through the introduction of immersive feedback, related to the properties of elements making up an architectural space.

### Goal

The goal of this thesis is to enable a new process, **experiential storytelling**. This type of simulation would keep architects more in touch with the complexity of the environments which built form creates. There are three main components in this process: modeling, manipulation and navigation. A detailed look at these components will reveal the differences from the traditional design process.

*We cannot hope to equal the speed and flexibility with which the human mind follows the associative trail, but it should be possible to beat it decisively in regard to the permanence and clarity of the items resurrected from storage.*



Vannevar Bush

*Approximately 95% of the information we use is not in a machine-readable form.*



Hewlett-Packard

### Fields of study

Understanding **perception** is critical for the research done in this thesis. Architectural experience is interpreted through one's perception of the environment. This thesis divides perception into two distinct processes: **assimilation** and **interpretation**. Assimilation is an objective, physiological process. Interpretation is a subjective, cognitive process. Both processes have a certain field of scope, or bandwidth, associated with them. **Immersion** occurs when the bandwidth associated with assimilation is utilized above a definite threshold. **Engagement** occurs when the bandwidth associated with the interpretative process is used above another threshold. **Motion** is critical to enable and understand both, assimilation and interpretation. **Semantics** are important to understand the interpretative process. Each notion is related to architectural experience and the relationships among them are analyzed.

### Methods

This thesis offers a method to **quantify** architecturally important properties of the environment, in order to enable their simulation. It is critical to make the creation, analysis and simulation of semantic

properties possible. Those semantic properties are based on the subjective cognitive process of interpretation. The main idea behind the quantification method is to find very narrow criteria of analysis. The more specific the criterion is, the easier it is to allow a quantifiable characterization.

### Approaches

This thesis deals with the simulation of architectural experiences. It analyzes architectural properties of the built environment. Then it assesses how these properties are perceived and interpreted. After understanding the perception process, an effort is made to determine necessary stimuli for compelling architectural experiences. Having determined those stimuli and minimum thresholds, the next step is to critically review existing technologies. This review reveals how present devices can simulate architectural experiences by providing the defined stimuli.

Analysis is performed both on hardware and software. Hardware is approached as recommended intuitive input and relevant output.

*Pick battles big enough to matter, small enough to win.*



*Jonathan Kozol*



Software is approached as interface linking and necessary data structure to assure desired functionality. The three-dimensional manipulating system, developed in this thesis, provides a concrete, novel example of an alternative process for picking and manipulating objects.



## 2. Existing conditions

An artist's **medium** can be very much part of the artist's message. Van Gogh achieved a deeper impact with his images of sunflowers, painted with thick, three-dimensional oil paints, than he could have with watercolors. On the other hand, countless watercolorists capture the watery, transparent serenity of harbor scenes more effectively than they could with oils. Architects, as all artists, are influenced by and take advantage of the medium's physical characteristics to achieve aesthetic objectives. Not using three dimensional representations of their work, they often rely on graphic, two dimensional models in their design decisions.

*The power of the visible is the invisible.*



*Marianne Moore*

When humans **pre-visualize**, within the realms of imagination, the environment that one "sees" already has experiential character. In the design process the experiential information fades in the translation. This phenomenon, characteristic of present visualization techniques, pertains to the design process carried by a single person as well to communication between people working on the same project. Conventional media are restrictive as to the type and amount of information they can convey.

Displays, regardless of medium, are mostly static and two dimensional. In the process of emphasizing some aspects in design or presentation, there are too many other facets that are sacrificed. Even the digital medium, as used until now, carries fundamental drawbacks. The **input** is counter-intuitive; mice, digitizers and even pens are restricted to a non-material two dimensional space.

In some recent studies designers were asked to tape voice comments of what they do while designing. Those using traditional paper medium were talking about the semantics of their work, while their CAD colleagues were talking mostly about the commands they were using on the computer. The results demonstrate that the digital medium is not, for the most part, as transparent as one would like. An architect designs mostly **3D** objects and thinks three-dimensionally. At this point, though, there are no intuitive paradigms for having direct and intuitive access to the third dimension. Applications, like the popular AutoCAD, high-end modelers like Alias, optimized modelers like MultiGen, or advanced packages like SoftImage and Wavefront - do not rely on an intuitive input of spatial coordinates. Rather, they rely on **construction planes**

*Computers are useless. They can only give you answers.*



*Pablo Picasso*

*The uselessness of computer drawings in design is precisely their structured nature.*



*George Stiny*

*The usefulness of computer drawings is precisely their structured nature.*



*Evan Sutherland*

*Technical feasibility and intellectual interest do not suffice to make computer methods advantageous.*



William J. Mitchell

*Societies have been shaped more by the nature of the media by which men communicate than by the content of the communication.*



Marshall McLuhan

and views that do not take full advantage of powerful human skills like eye-hand coordination in a true three-dimensional space.

The same constraints apply to the **output** as well. The computer screen is flat and provides limited depth perception with the use of perspective, aerial perspective, animation, or a combination of those. As opposed to traditional media, existing **digital** implementations like AutoCAD favor a true three dimensional relationship between the elements in the database at the expense of an awkward input process. It quickly obtains diverse points of view of the same object enabling turn-tabling and fly-throughs. This process, however, loses the semantic qualities, critical in the initial phases in the design process, as they reveal a number of subjective interpretations.

Regardless of the media used, present solutions offer hard compromises for architects. Bottlenecks are formed in the design process and the final product becomes involuntarily removed from the original concept. It would seem useful to benefit from a tool that provided complex 3D form

as well as semantic, experiential input and output at all stages in the design process.

Until now, an effort has been made to **engage** the viewer by saturating the **interpretative** process bandwidth. This direction is useful as initially engagement and incorporated semantics are weak in the digital medium. Technology, however, has reached a level that it can provide more bandwidth at the **assimilation** level. This direction opens the door to **immersive** simulation. Immersion, when linked with engagement, provides the ingredients for compelling experiential simulations. The effort to understand and produce a multi-dimensional experiential sketch, rather than a conventional, form oriented, 2D representation, brings one closer to the real **impact** of built form.

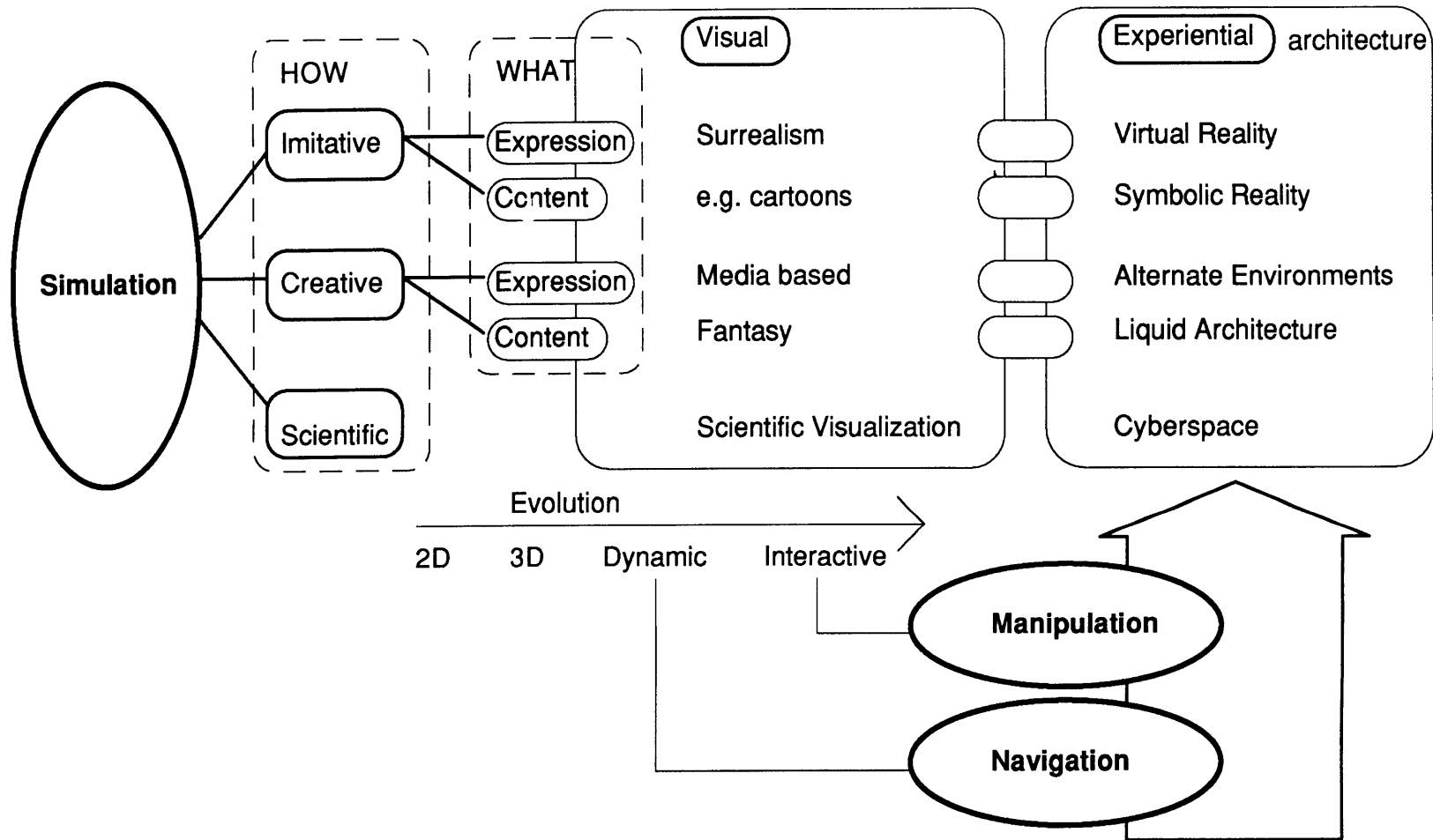
The essence of architecture is experiential. In the design effort of new and existing environments, one should strive to provide a meaningful experience of "**place**". Having feed-back early in the design process on the experiential qualities of a proposed environment can substantially improve esthetic decisions.

*We are likely to see a multiplicity of quite different global villages -- all wired into the new media system, but all straining to retain or enhance their cultural, think, national, or political individuality.*



*Alvin Toffler*

Providing a complex framework for choosing among design alternatives is most important to the effect of the visualized environment in **early stages** in a design process. Major conceptual decisions about siting, orientation, massing, circulation, functionality, and organization are usually made at a very early stage and have an enormous impact on eventual performance. Later choices focus on refinement of detail within increasingly well-determined frameworks, so there is a decreased potential to achieve significant improvements.



CONTEXTUAL OVERVIEW OF EXPERIENTIAL SIMULATION



### 3. Proposal



*The chart attempts a classification of the forms of architecture encountered in various immersive simulations. The criteria of the classification looks at the expression and content of the simulated environments.*

*Were it not for departures from, or experimentation with, previous artistic norms ... we could never recognize the profile of a new style.*



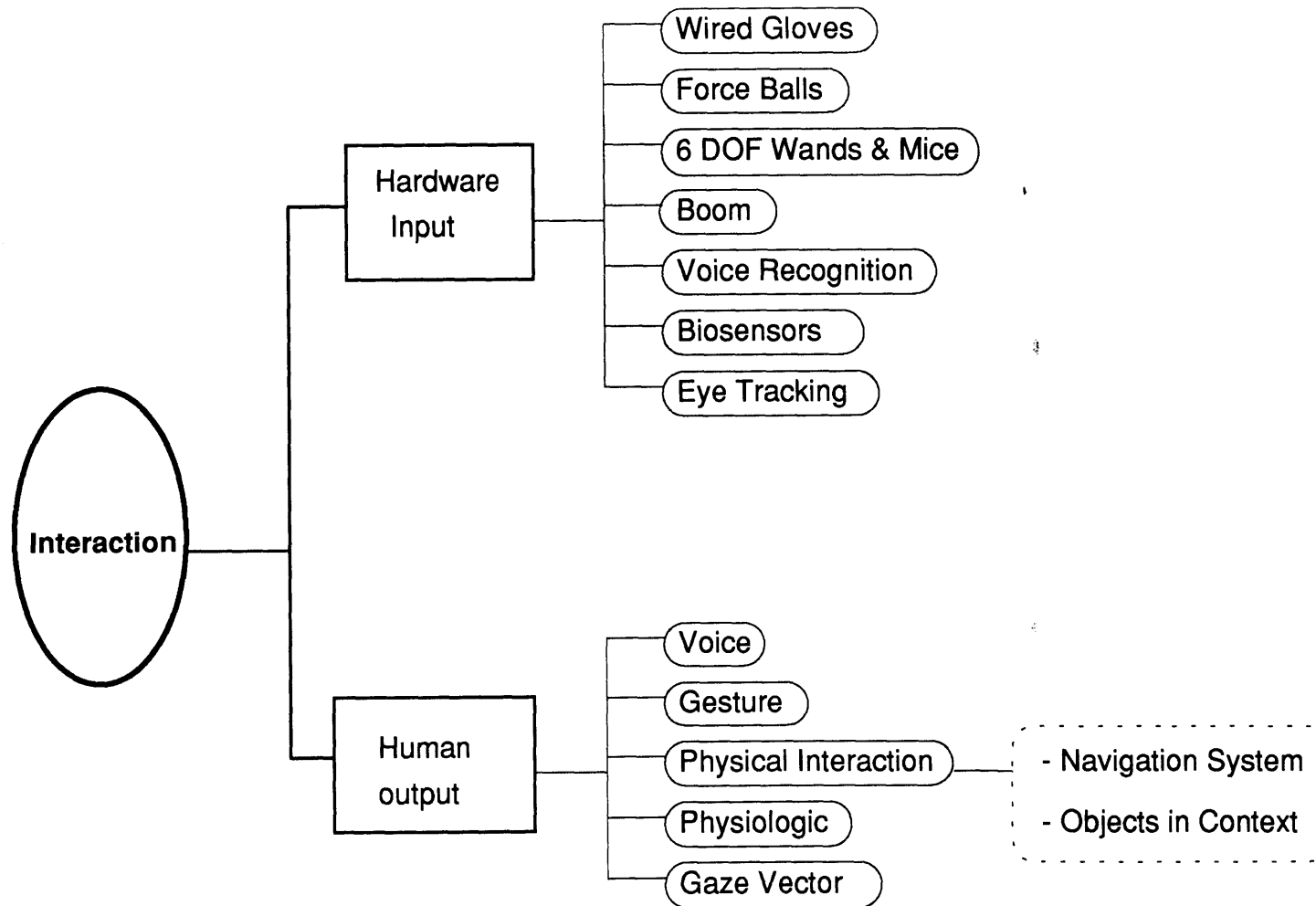
Susan Sontag

The goal of the proposed design environment is to enable an architect to  
1) very quickly and intuitively generate a complex three dimensional environment and 2) test the experience associated with those spaces.

This tool is based on a powerful graphics computer, the Onyx system, manufactured by Silicon Graphics Inc. It allows for intuitive input and relevant output. This high-tech design workstation is based on a "Reality Engine" graphics board and various virtual reality type peripherals.

#### 3.1. Input

The input provides direct information on all six degrees of freedom by using a field localizer tablet. It relies on intuitive spatial eye-hand coordination. The position and motion can be associated with any synthetic object, camera or light in the scene. A vocabulary of spatial elements and customized interfaces assist in an **intuitive** and **rapid** interaction. The necessary technologies are already developed. The goal can be achieved by **linking** the pertinent technologies. Interfaces



## INPUT DEVICES



*These are the main peripherals for input. They are directed to specific human output capabilities.*

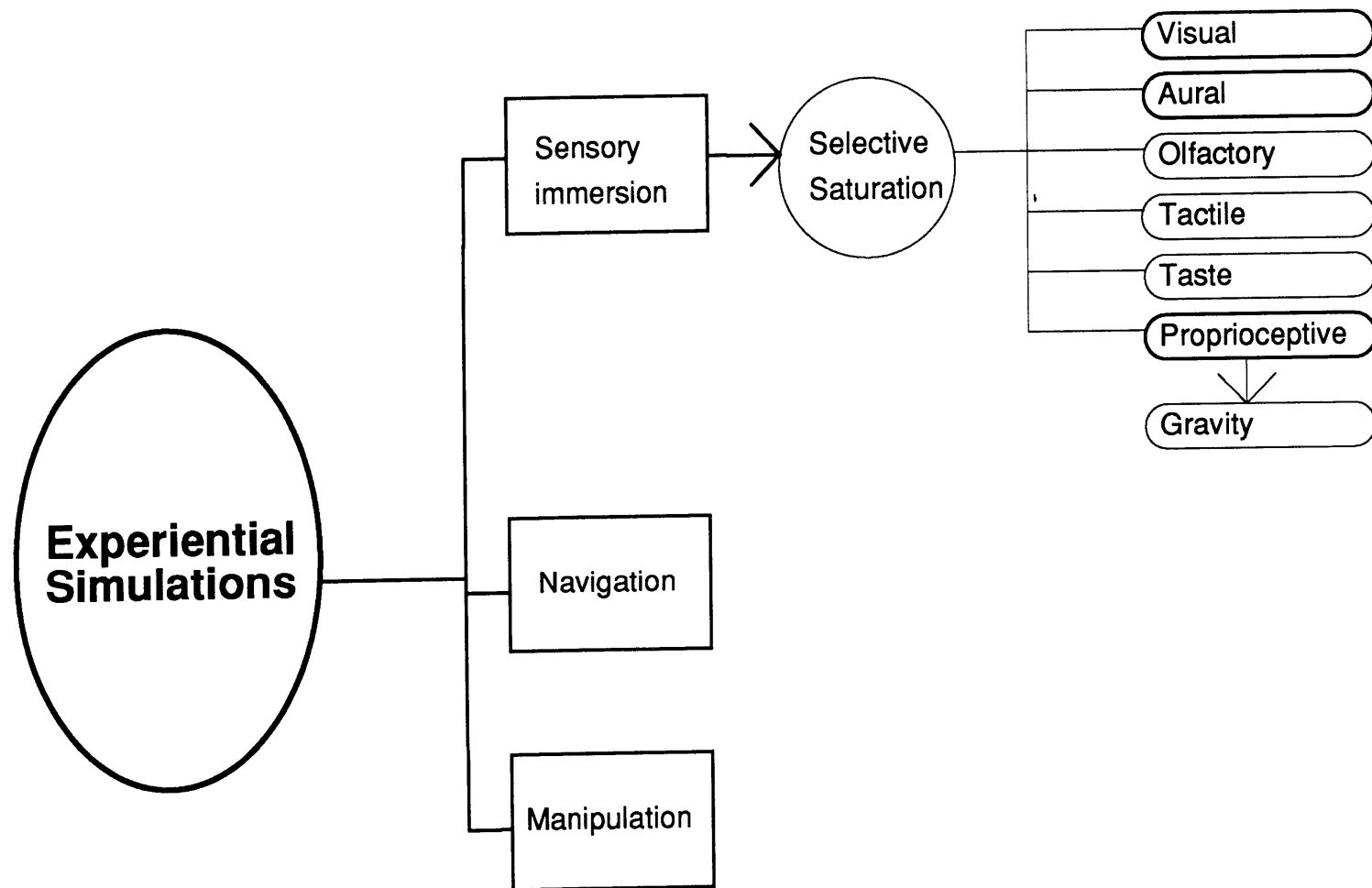
*Things change. But unfortunately, all too often as one becomes more experienced and successful, one's rationale becomes more convincing in explaining why new things can't work.*



*Primo Angeli*

join those peripherals assuring effective functionality while minimizing necessary customization. The chart above shows the various off-the-shelf peripherals that could be used to provide the most intuitive input for different tasks.

In addition to traditional means of input, such as typing and sketching, voice, gesture, physical interaction or physiological processes are used as well. These input devices are intuitive for different tasks. **Wired gloves** offer positional and directional input and can be associated to gesture recognition software. **Force balls** offer three translational and three rotational inputs with variable velocity as determined by the exerted force. Six degree of freedom devices (6DOF) offer a continuous or virtually continuous positioning associated to any object, camera or light source. **Microphones**, associated with voice recognition software, allow for a simple understanding of voice commands. A variety of **bio-sensing** devices offer direct input that could be linked to gaze vectors, for an "understanding" of where the subject is looking. Other sensors can be linked to certain muscles to detect contractions. Alternative bio-sensing devices could even detect and discern cerebral waves, for futuristic



DETERMINANT FACTORS OF EXPERIENTIAL SIMULATION



*The critical dimensions for any experiential simulation enable the subject to be immersed in the simulated environment. Functionality is assured by allowing interaction with the environment in the time/space continuum. This translates into navigation and manipulation.*

*There is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in the introduction of a new order of things.*

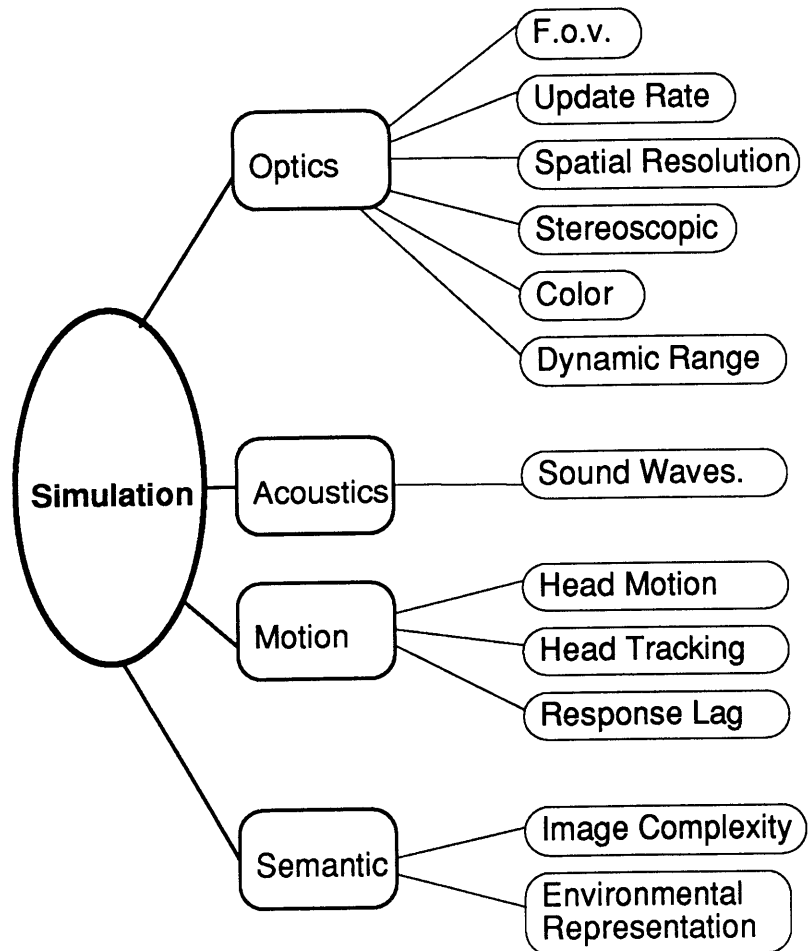


*Machiavelli*

implementations that would enable the system to execute a command that was merely thought... These devices implement available technologies and take advantage of the various ways in which the user interacts with the system.

### 3.2. Output

The output of the proposed design tool provides relevant feedback on selected aspects of the design. It is, in this sense, much more comprehensive than existing design systems. Through **immersion**, it reveals the experiential qualities of the designed environments. As established, immersion occurs when stimuli are available for assimilation above a certain threshold. A critical assessment of this threshold is needed to discern among stimuli and define pertinent formal and experiential simulations from an architectural point of view. From this perspective, the important senses to be provided with stimuli are **visual**, **aural** and **proprioceptive**.



Minimum	Maximum
H 60 degr.	H 180 degr. V 135 degr..
12 Hz	60 Hz.
4 arc min.	0.6 arc.min.
?	
24 bits	3 channels x 17bits
?	$10^5 : 1 = 50\text{dB}$ <u><math>= 17\text{bits}</math></u>
?	3D
?	20 Hz - 20 Kz
?	
?	
?	
?	photo-realistic

750 Gbytes/s

36,000 x 28,000  
pixels on 180 degr.

overlap F.O.V.  
conveyence  
brain processing  
focus

### CONDITIONS FOR IMMERSION



*Immersion relies on selective saturation of sensorial assimilation. Recent research has determined the maximum bandwidth available for input. Experiments give (subjective) clues on minimum acceptable stimulation.*

*If you build castles in the air, your work need not be lost; that is where they should be. Now put the foundations under them.*



*Henry David Thoreau*

Visualization and coordination are enhanced by providing a stereoscopic display as one output. Important characteristics such as resolution and perceived field of view are considered.

Directional clues are intensified with a 3D sound system and a motion base that simulates different gravitational pulls. As it has been argued, motion is an indispensable part of the architectural experience, therefore, relevant proprioceptive feedback would be an integral part of the system. This can be achieved with adequate approximation by incorporating a motionbase into the system. These motion simulators are available and have traditionally been developed for the flight simulation and entertainment industries.

A motionbase, as exemplified in simulation rides, conveys the sensation of movement through a visually simulated space. The impact inspired by the union between the motion and imagery creates a believable compelling experience. This medium, applied to architecture, could dramatically influence the design process and the experiential qualities of the studied or proposed built environments.

Motionbases simulate movement by altering the orientation of the gravity force or introducing new forces. The idea is to approximate the result of the forces that act on one's body when in motion. When one walks, one raises and lowers the center of gravity of the body and muscles contract and then relax to do so. This type of movement is obvious, hard to simulate and has little bearing on the architectural experience. What seems more relevant is to be able to simulate movement at higher speeds.

With existing flight simulation techniques, the higher the speed of motion, the more efficient the simulation can be, regarding both visual and proprioceptive feedback. When one moves at higher speeds, the relevant forces are inertia and gravity. The intensity of the inertial force is determined by the acceleration or deceleration of the moving subject. The direction of the vector corresponds with the direction of movement. The intensity of the gravity force is constant for all practical purposes and the direction is pointing "down". Therefore, if a simulation rotates one's body in the sagittal plane forward (nose pointing down), and keeps the

*In practice, the balance is likely to shift gradually from storage and retrieval to generative systems as processing speed increases and as empirical design knowledge gives way to more theoretically structured knowledge*



*William J. Mitchell*



*The most incomprehensible thing about  
the world is that it is comprehensible*



*Albert Einstein*

simulated visual horizon constant, the subject feels decelerated or moving backwards, depending on context. This is because the subject interprets the change of direction in the resulting forces exerted on his or her body as an inertial force forward. This demonstrates how gravitational pulls correlated with body position and specific visual clues can simulate inertial forces.

It is also possible, with additional forces, to simulate the change of direction in the gravitational pull. Introducing a force on the body in the sagittal plane from front to back and correlating with visual clues depicting the horizon above the head would simulate a fall. The additional forces can be provided either by rotational or centrifugal forces, or by translations of the motionbase. The translational forces have the flexibility to rapidly change as needed but are hard to maintain for more than a few seconds in a specific direction within a confined space. Special care has to be taken to best match visual and proprioceptive clues. This is particularly important and challenging in real-time simulations. Not only the system has to have a lag time of no more than a

few hundredths of a second but it should also adjust for the physical limits of the motionbase itself.

### 3.3. Libraries of objects

The generation of complex, three dimensional environments must be efficient in order to be useful to a designer. The process of creating an environment is optimized by providing a pre-defined, yet customizable **library** of objects. The user is free to choose from a number of default **objects**, with a number of default **properties**, that have default **values**. The objects in the library have basic quantifiable architectural properties (e.g. geometric, color, texture, acoustic and motion). The default value of these properties are average or neutral to ensure rapid prototyping. For the success and practical application of the tool it is critical to offer the freedom and flexibility to create and experience a wide variety of environments in various ways. Different users, architects or clients, are interested in different forms or studies, depending on the phase of the project and their interest. The library systems are developed to provide the user with great freedom at many levels of operation: a) to change or customize the default objects in the library; b) to associate different

*A breach has been made with the past, which allows us to envisage a new aspect of architecture corresponding to the technical civilization of the age we live in.*



*Walter Gropius*

*Since finding out what something is largely a matter of discovering what it is like, the most impressive contribution to the growth of intelligibility has been made by the applications of suggestive metaphors.*



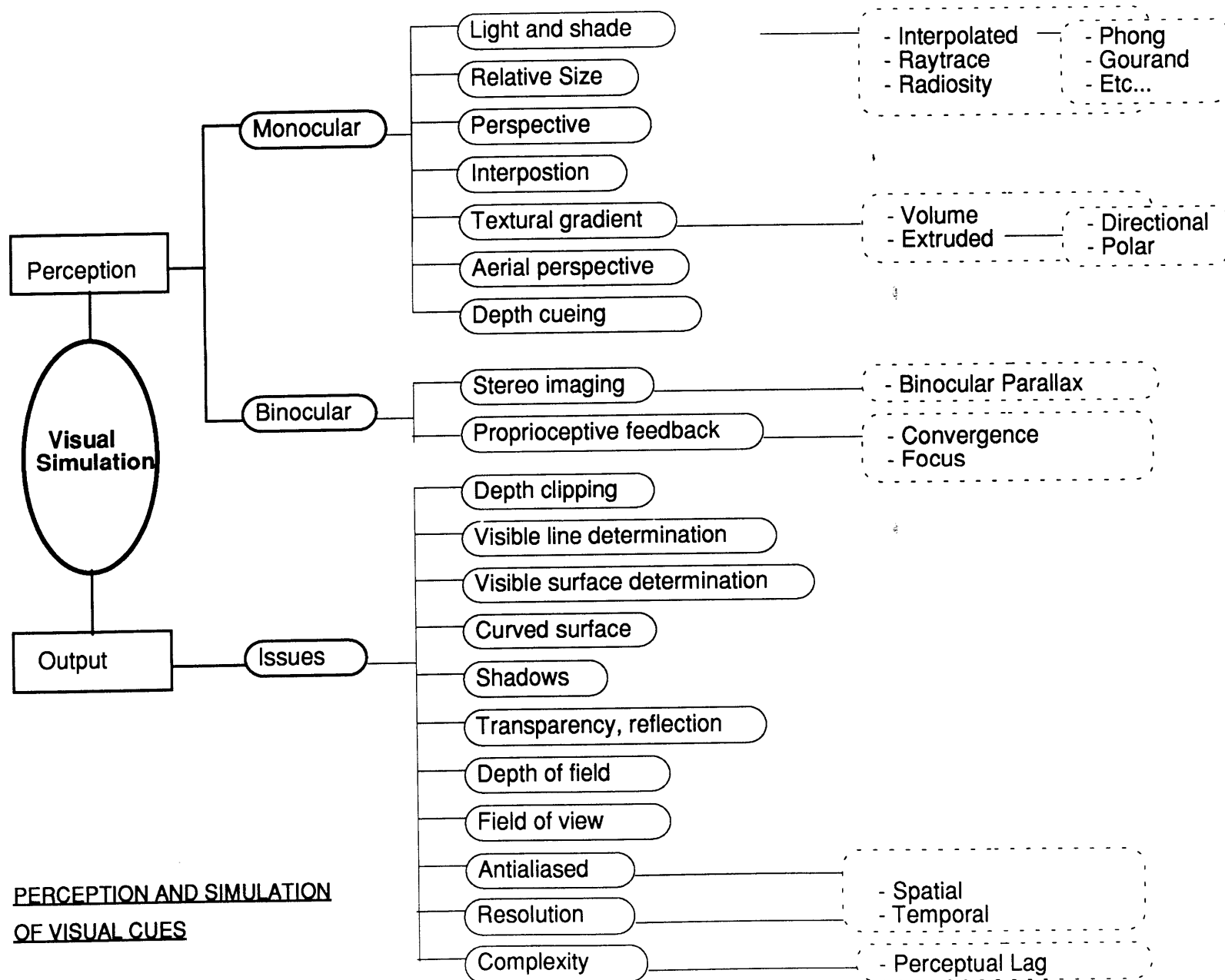
Jonathan Miller

projects with different object libraries; c) to add, delete, change or create new properties, depending on the phase of the project or specific study interests. This also allows for dynamic change of the hierarchy structure of properties, as some depend on others. d) to change the fields (typically consisting of quantified numerical values) associated with each property.

A graphic user interface is used to visualize and dynamically customize the relationships between objects, between properties, and between objects and properties. These relationships determine the **behavior** of the objects. Scientific visualization applications, such as Iris Explorer, developed by Silicon Graphics Inc., offer a similar basic data structure.

### 3.4. **Experiential storytelling**

In traditional film-making, two-dimensional sketches represent the way images change over time. This process, called "storyboarding", relies on "freeze-frame" sketches to convey a motion story. By interpolating the images, one can pre-visualize the motion picture. Applied to architectural design, this process enables the architect to sketch views along a motion path, to explore the significance of the built form in an environment and as





*The chart depicts monocular and binocular visual cues from the 3D environment. The same cues are presented in terms pertaining to computer graphics imaging.*

an environment. Current architectural computer applications consume a large amount of design time yet offer limited information. Animations in visualization have become popular with the use of the computer in architectural offices, but their experiential feedback is limited. This feedback would be significantly more successful with immersive technologies. Immersion enhances motion as motion enhances immersion. **Experiential storytelling** relies on the combination of immersion and motion. During this process the designer or client sits on a motion chair in front of a large field of view display.

*Imagine a dim room, almost dark. On a panel in a corner, a few colored LED signals flash, signaling buttons waiting for commands. Somebody reaches over and pushes the big green circle with the "engage" label. Suddenly, light floods the room. It is coming from a large display that covers almost half of the room's perimeter. The people inside reach out on a shelf and each take a pair of thick glasses. A few seem to have their own, as they reach in their pockets. Now, the design team is ready. In the following hours they have to conclude the presentation. Only a few more adjustments are needed to fine-tune the design. A couple of keyboard strokes are heard in the background and an image fills the display. The image looks blurry. As everybody puts their glasses on, they are able to see high resolution, color,*

*stereoscopic images forming in space, in front of the circular display. They seem to be right there, on the main downtown artery. The room is filled with the sound of the traffic, synchronized in time and space with the images on the screen. Floating in space, in front of them, is a literally transparent graphic user interface. The project leader points a pen to the "navigate" icon on the menu. This deactivates the modeling and manipulation modes and opens up a hierarchy of options ..He chooses "car", "automatic pilot" and "subdue rough road feedback". The designers seated on the motion chairs feel a swift acceleration as they head down the avenue...*

#### **3.4.1.   ■ Immersion**

Immersion is the most critical aspect in experiential simulations. It is achieved by maintaining a subjective threshold of the assimilation bandwidth. Therefore, immersion is obtained by selectively saturating some of the senses. Total immersion is indistinguishable from reality. It fills the full bandwidth of the human perception. Contemporary technology is not yet developed to provide total immersion, for any cost. and will be problematic even in the future. With this in mind, the parameters of the proposed three-dimensional design tool reflect the relevant aspects from an architectural point of view, to be simulated.

Which senses and how much of their bandwidth are covered? Which technologies provide the necessary output and at what level is the tool cost-effective for implementation? Humans have six senses that respond to stimuli. The five basic senses are visual, aural, olfactory, tactile and taste. The sixth sense, and probably the hardest to simulate, is proprioceptive - that senses the status of our body, mainly its position. In the human mind, the perceived output from a scene flows to the cognitive processes for interpretation.

The parameters of a "ultimate motion imaging system" has been recently determined by a series of experiments. [Shostak] The human visual system has a horizontal field of view of 180 degrees and a vertical field of view of 135 degrees. This cone of vision provides stimuli to the receptors on the retina. If these receptors were uniformly distributed over the full retinal field, their resolution would be approximately 0.65 arcmin. The characteristics of the human visual system, as they relate to simulation, were presented at the 26th annual SMPTE Advanced Television and Electronic Imaging Conference (February 1992). The particulars of this research are the following :

**field of view** -  $1.5 \pi$  steradians,  
**color** - 3 channels (17 bits/channel),  
**stereopsis** - 2 channels,  
**dynamic range** -  $10^5$ , frame rate - 60 Hz,  
**resolution** - .5 arcmin.

based on these figures, simple mathematical calculations yield an equivalent display of 36,000 x 28,000 pixels spread over a truncated hemispherical screen. With the refresh rate included, the available **bandwidth** is 750 Gbytes/s. This is well beyond the means of today's technology to calculate and display in real-time. A compromise is reached by not covering the full available bandwidth, but by reaching the immersive threshold. The question then becomes what the minimal values and bandwidth are which would provide an immersive environment and sufficient information for a compelling architectural experience. Flight simulation specifications recommend 60 degrees as minimal horizontal field of view. A refresh rate of 60 Hz per eye can easily be obtained. The update rate is more difficult because of the high computational demands. Recent research [Piantanida, pg. 50] shows that update rates of and above 12 Hz allow the perception of smooth motion as the eye movement reveals smooth pursuit of the image. Visual resolution is a more

*There is mystery enough in the wonder  
of (the body's) creation and operation  
without creating a mystique of ignorance  
around what can be known.*



*Kent Bloomer*

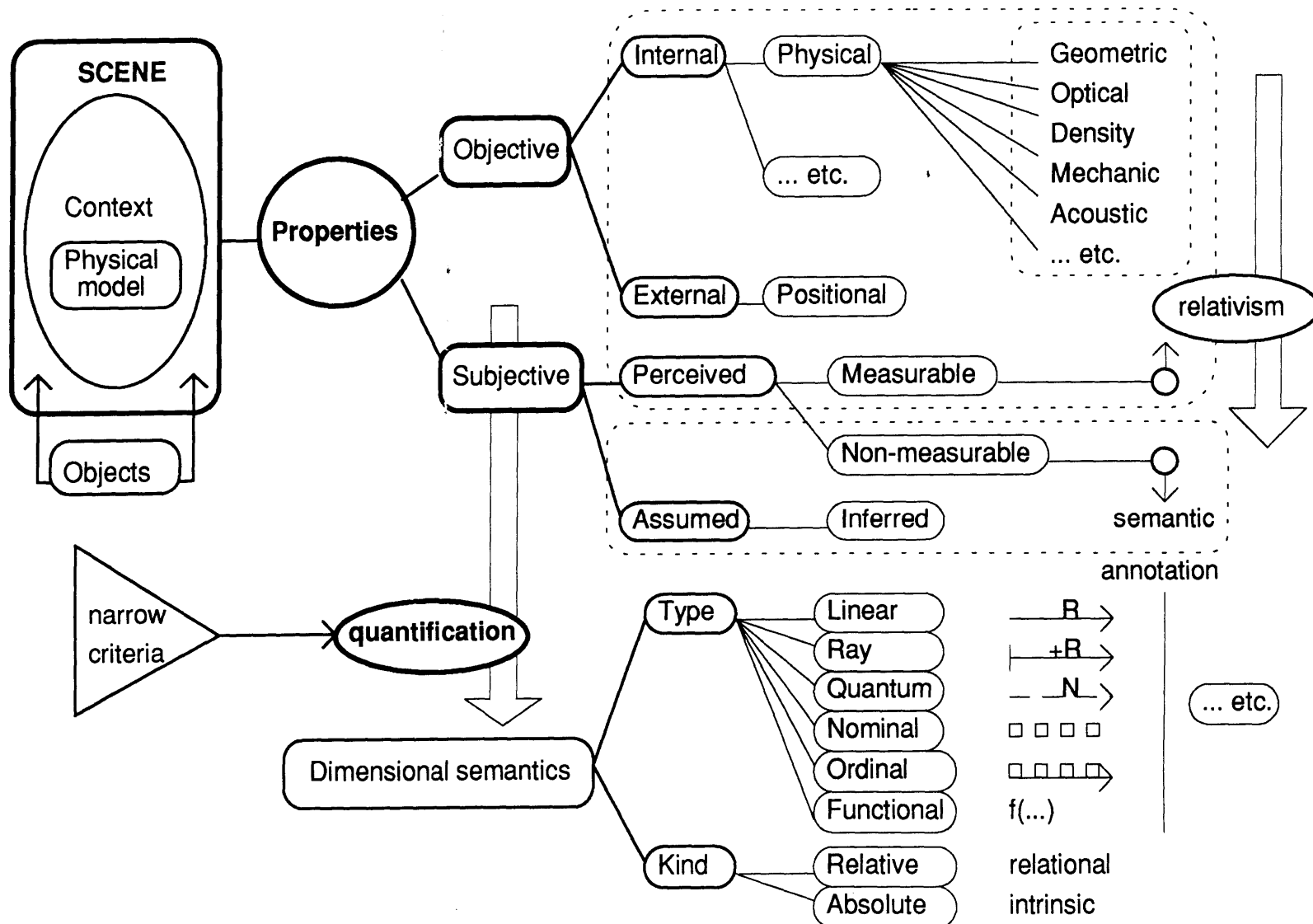


*The starry heaven that we know in visual sensation is inside us. The external starry heaven that we believe in is inferred.*



*Bertrand Russel*

subjective issue. There is no specific threshold, as the visual cues increase proportionally with increased resolution. Through empirical research and testing, it is concluded that typical head-mounted displays do not offer sufficiently high resolution for immersion. The VPL EyePhone based on LCD technology provides a resolution of 13 arcmin on the retina for each pixel, which is roughly the equivalent to having 20/200 visual acuity on the Snellen eye chart [Piantanida, pg. 45]. Better visual cues are obtained in projection systems. The drawback of this system is that head movement is not compensated, therefore, less depth information can be conveyed due to the lack of motion parallax.



## PROPERTIES OF PHYSICAL OBJECTS



*The context and the model within define the scene. The objects have specific properties and provide a specific output. The perceived output from the scene has an objective aspect - assimilation, and a subjective aspect - interpretation. The more subjective the properties, the more they necessitate a quantification process to enable their simulation. The quantification classification is based on "Cyberspace - the first steps".*

*The arts are neglected because they are based on perception, and perception is disdained because it is not assumed, to involve thought.*



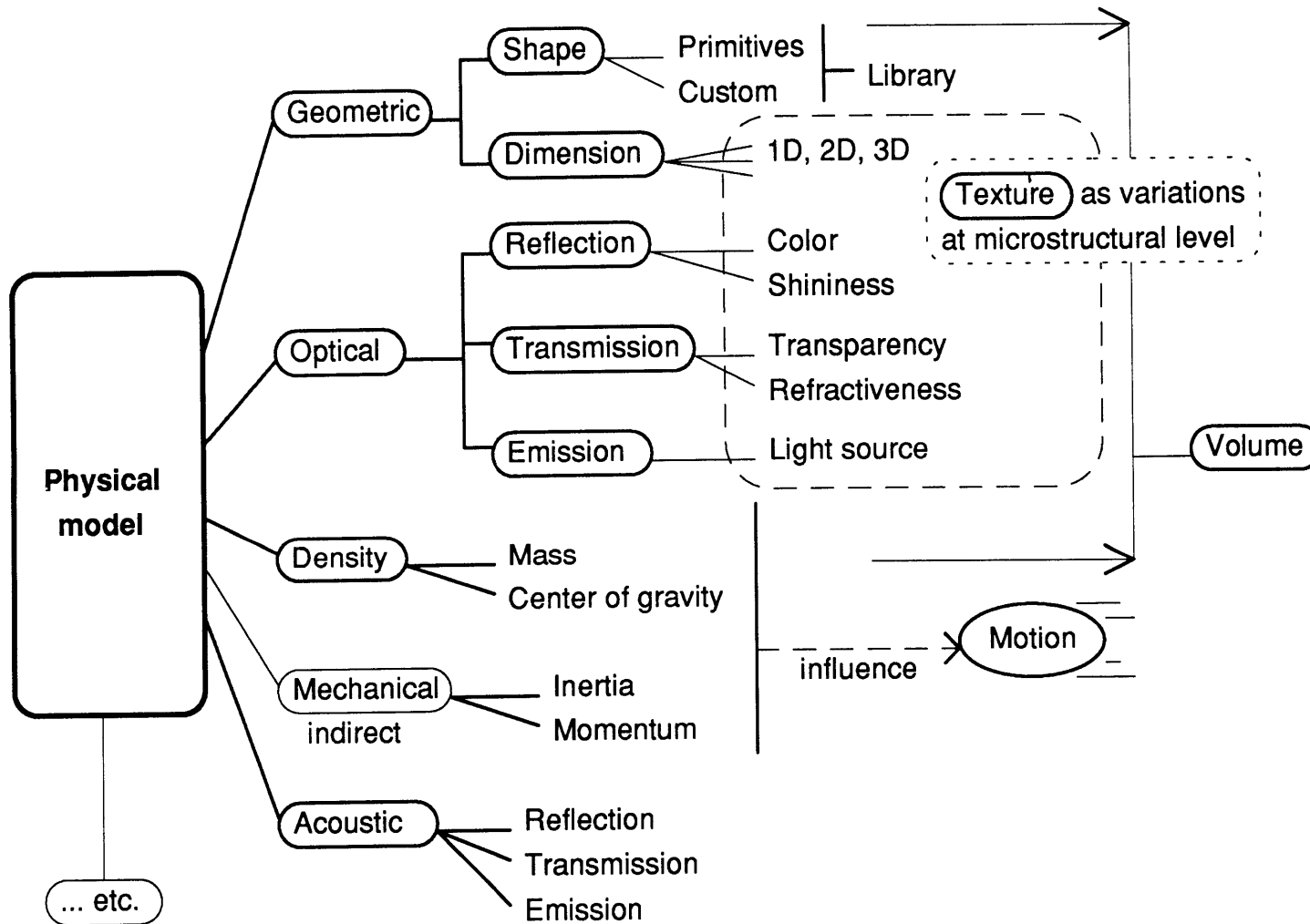
Rudolf Arnheim

#### 4. **Experience of space**

All definitions of architecture, classic or modern, poetic or pragmatic, talk ultimately about the **experience** of architecture. Even when it is not acknowledged directly as a goal, it is the experience that provides the **interface** between all living creatures and their environments. The meaning of architecture reflects an interpretation of how one experiences the environment. The understanding of architecture from this vantage point relies on the cognitive process of information that flows from our senses. Cognitive associations, **semantic** knowledge, provides an individual with the basis for interpretation of an inhabited space. The process of experience relies on **perception**, or **assimilation** plus **interpretation**.

##### 4.1. **Perception**

In order to understand perception, one must study not only the characteristics of the physical world, but also those of the perceiver. British philosopher John Locke distinguished between **primary qualities** and **secondary qualities**. Primary qualities consist of *assimilated* properties actually present in an object, for instance color, dimension, and



# INTERNAL PROPERTIES OF PHYSICAL MODELS



*This is a simplified representation encompassing properties considered important from an architectural point of view. Any material object has an infinite number of properties, as the properties can be defined in numerous ways. Therefore, it is important to assure flexibility of property representation in the respective data structure.*

*We have now become aware of the possibility of arranging the entire human environment as a work of art, as a teaching machine designed to maximize **perception** and to make everyday learning a process of discovery.*



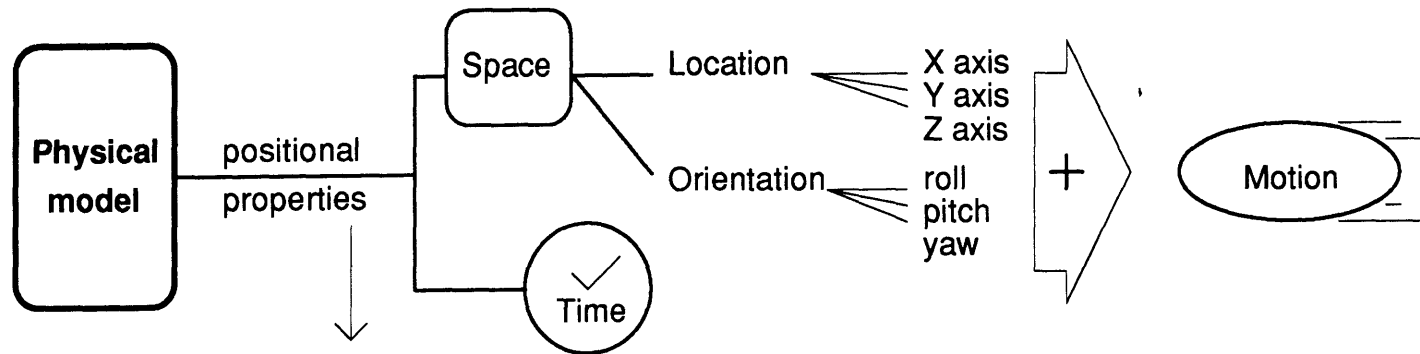
*Marshall McLuhan*

surface texture. Secondary qualities, on the other hand, are *interpreted* qualities present only to the individual perceiver, such as massiveness, dominance, warmth, and beauty. The existence of secondary qualities, Locke said, depend upon one's perception of them [Sekuler, pg. 10]. They rely on cognitive associations; the subjective interpretation of the world around an individual. Due to their interpretive nature, secondary properties are more difficult to quantify than the primary ones, but are nevertheless essential in defining architectural experiences. This thesis argues that these secondary properties are more important to the understanding of built form than the primary properties since they can be manipulated by the user or the designer. An understanding of how one can simulate and manipulate these properties can be immensely informative in the architectural design process.

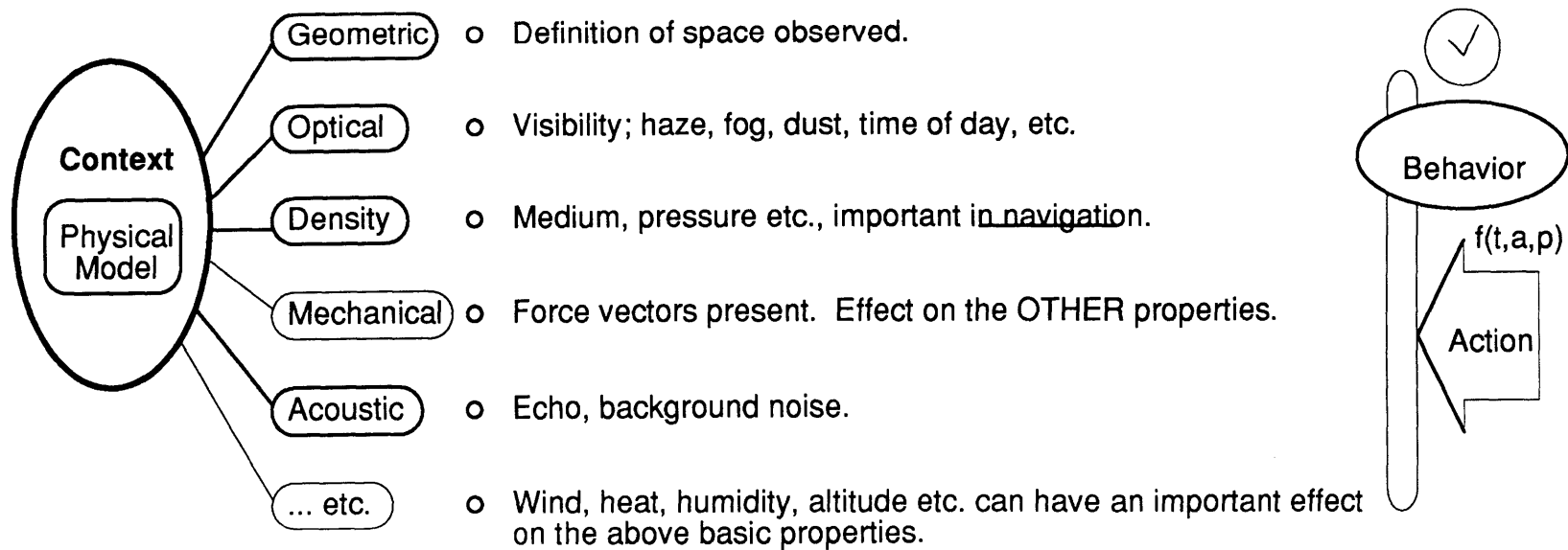
#### **4.1.1. 📖 Phenomenal approach to perception**

As previously noted, human perception relies upon assimilation and interpretation of information. There are several psychological approaches to the understanding of perception. These approaches differ from each other by the behavioral reaction to stimuli they use as a method of

## EXTERNAL PROPERTIES OF PHYSICAL MODELS



## CONTEXTUAL PROPERTIES





*Properties of the context are neither internal or external as there is no higher level in the structure of physical objects*

evaluation. This thesis uses the phenomenal / naturalistic approach to the study of perception, since this approach maximizes usable information from an architect's point of view. The approach is "phenomenal" inasmuch as the evidence used by it consists of one's conscious experiences. It is "naturalistic" in the sense that the evidence concerns responses to the stimuli occurring naturally within the environment and that there is no attempt to modify these stimuli or to create artificial ones. The phenomenal / naturalistic approach is based on the most easily obtainable data - experiences evoked by occurring events [Sekuler, Blake, pg. 16-23] Through perception one tries to better understand experience, architectural experience in particular. Such experiences might include the rhythm of edges while moving through an urban environment, a glimpse of a crafted detail, the massiveness of a building, or the feeling of "place".

#### **4.1.2. ■ Phenomenal approach to architecture**

In his book, "Archetypes in Architecture", Thomas Thiis-Evensen studies the environmental and architectural **experience** to understand the universality of architectural expression. In an effort to quantify

architecture, he defines architectural archetypes -- "the most basic elements of architecture" which he identifies as **floor, wall** and **roof**. He emphasizes the importance of "a more reliable basis for the emotional content of architecture" and argues that a phenomenological understanding of architectural form might lead to a more thoughtful and accurate architectural aesthetic, to replace professionals' and lay persons' "generally subjective 'feelings' about buildings." Through an extensive descriptive study of a variety of architectural examples, classical and modern. Thiis-Evensen concludes that any building can be interpreted experientially in terms of floor, wall, and roof. His main aim is to describe the different kinds of environmental experience that variations of each of these three elements sustain and presuppose. It is possible, he argues, to arrive to a common language of architectural form which we can immediately understand, regardless of individual or culture.

Floors, walls and roofs separate the architectural world into interior and exterior in different ways. Different architectural styles and cultural traditions may interpret this separation through different degrees of opening and closure. These can be explored through three "existential



expressions of architecture" -- **motion**, **weight** and **substance**. Motion refers to the sense of dynamism or inertia of the architectural element (expansion, contraction, balance etc.). Weight expresses the sense of heaviness or lightness of the element and how it relates to gravity. Substance refers to the material sense of the element (soft or hard, coarse or fine, warm or cold etc.).

*The design of complex, varied forms  
that are adaptable over time and  
nevertheless easy to control and to build  
demands new methods and skills.*



*N. John Habraken*

The criterion that Thiis-Evensen applies in his study and classification are to a great degree **quantifiable**. This opens the possibility of creating interactive and dynamic links among classified examples. This thesis follows Habraken's advice and approaches design by studying "environments with a high degree of spatial complexity to find out what their structure is and what process could make them come about." In order to control the complexity of the forms, the proposed tool represents the environment quantified through very narrow criteria.

#### 4.1.3. ■ Form

Regarding the perception of form, there are two opposite schools of thought. The **structuralist** approach to form perception states that complex mental processes - ideas and perceptions - are created by combining fundamental components. According to this view, simple sensations constitute building blocks of perceived form. In many areas of science, progress goes hand in hand with this analytical approach - one that breaks the phenomena of that science down into appropriate components. This approach harbors the danger of overlooking the systemic properties which would be revealed only by looking at the whole. The developed and refined relationships between components are especially important in architecture. The majestic effect of an ancient Greek temple or a Palladian villa lies in the relationships among the components of the whole. Adding or removing any one element would certainly ruin the perfect balance that raises the building to a masterpiece status.

At the other extreme, **Gestalt psychologists** emphasize the overall structure or pattern as the major determinant in form perception - "The

whole is greater than the sum of parts". Max Wertheimer noted that "...when many stimulus elements are present simultaneously, they tend to become grouped or organized perceptually into distinct patterns." *[Wertheimer, pg. 115-135]* Although various organizations are possible, people would see one particular organization or pattern. This realization limits the possibility of simulation necessary for an implemented experiential design process. A thorough analysis of the subjective perception elements requires their quantification. This can be achieved only by having criteria sufficiently narrow to allow binary characterizations (yes or no) or specific numerical values.

The approach of this thesis balances between the structuralist and Gestalt positions. When designing the parameters for a new architectural design tool, one should look at perception of built form through very narrow, elementary criteria. This permits a more thorough analysis in search of spatial and experiential archetypes. It also makes quantification and clear classifications possible. Systemic and behavioral properties become more relevant by linking and grouping these criteria in meaningful ways. Focusing one's scope on certain aspects of perception

reveals unforeseen patterns that inform design decisions. This approach has been used until now almost exclusively for data visualization. Sometimes it had, more or less, a geometric representation associated with it in cyberspace solutions. In architectural design, it would be applied in reverse - a dynamic visualization of informative data associated with specific built elements and motion paths.

Phenomenological classifications of built form imply certain hypotheses about design, description, representation and manipulation of architectural knowledge. Empiricism is never pure. The question is about the substance of the rule, about the hypotheses subtended by its choice. *[Fleischer]* In "Grammatical Architecture?", Aaron Fleischer writes about the three kinds of knowledge that require accommodation: constraints, diagnostics and preferences. Constraints describe conditions that the exploration must meet and keep. Diagnostics describe the semantics of human vision: how you see, and what you infer from how you see. Preferences are the architect's constraints. The present values of the constraints, diagnostics and preferences describe the state of design. In

*The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them.*



*Sir William Bragg*

these terms, this thesis studies the feedback that diagnostics have on constraints.

In order to deal with the environment successfully one must be able to detect and to discriminate. Detection tells one that objects are present. Discrimination allows one to sort out important from unimportant information. Of course, what is important depends on one's needs. It is critical, however, that one carefully define the criteria used in discrimination as to be able to make informed, justifiable decisions even in subjective areas that involve semantics. Part of the task of designing the parameters of a design tool would be to detect the properties associated with designed environments and to critically discriminate among them.

#### **4.1.4. ■ Motion**

Experience cannot exist without motion. Without constant change and transformation, space and time are frozen, locked. Variances in time are a basic condition for life. To enable experience, motion is necessary on three basic levels:

### 1. Motion as part of the scene.

To enable perception, the environment must provide a continuous flow of information in a form that can be processed by the perceiver. This flux of stimuli shall be referred to as the **output from the scene**.

### 2. Motion as part of the perceiver.

To enable the sensing mechanisms to take advantage of the full bandwidth available to them. This type of motion shall be referred as **perceived output**. The perceived output is the information that is processed during assimilation.

### 3. Motion as part of the cognitive interpretation of one's senses.

This type of motion relies on bio-chemical motion rather than on mechanical movement at the macro level.

Of interest to this thesis are the first two types, motion as part of the scene and the perceived output. These qualities generally identifiable, mechanical, measurable variations of a location in space. The richness of an experience depends on the amount of information provided to the subject. This information can be at the assimilation level (primary qualities) as existing in the scene, or at the semantic level (secondary

qualities) as interpretations, cognitive associations related with the perceived environment. The more bandwidth associated with the overall perception of an environment, the richer the experience is. The human body and mind constantly strive to maximize the bandwidth available to the senses. Psychological experiments show that if the image that forms on the retina does not change over time, the visual perception fades to zero. The vision of frogs is limited in the sense that they see only objects that are in motion. Humans are constantly moving their eyes on apparently random trajectories to maximize the information reaching the brain. Humans are highly multi-tasking creatures. This capacity is maintained by a dynamic balance of reorienting the processing of information. A person may voluntarily orient his or her processing capacity toward something interesting. In addition, the human brain involuntarily shifts the focus to where there is an abundance of stimuli. A sound, even if it is not continuous or subdued, becomes "background information" after a time, as its parameters are predictable and present no interest. The cognitive processes are starving for new information. If it is not accessed, the attention shifts dynamically to the other senses,

extending their bandwidth. For example, studies show that subjects can hear better with their eyes closed.

In the experience process the subjective perception of space through motion is essential. Architectural experience is mainly determined by built territories and motion paths through them. Motion is the single strongest condition for understanding space. The surrounding environment is perceived and understood through movement at various levels. Motion as change in time is necessary to perceive stimuli that create an architectural experience.

For simulation purposes, an analytical understanding of territories and paths is necessary. Defining not only a vocabulary of forms, but also the movement paths through them becomes essential in both the analysis process and the generative design process. This vocabulary arranged in a digital library, may be retrieved rapidly to be used as building blocks in the architect's design process.



Combining those elements from pre-defined and customizable libraries could lead to generating easily controlled experiences of the built form. These associations are meaningful with respect to spatial relationships, suggestive paths through built environment, scale as it relates to time and space, etc. All of these are important building blocks for a synthesis or simulation of a complex experience.

#### 4.2. Interpretation

The preliminary sketches of a designer are sometimes called "empathic" sketches because they are meant to express not only the objective form of a product, but the subjective feelings and meanings as well. Such sketches represent the **semantics** which the designer wants to evoke in the viewer. Sometimes a fat, imprecise felt-tipped pen is the only tool that can capture the desired essence. Other times, a hard, fine pencil works best. Yet, with pragmatic architectural issues, the medium should not be obvious, lest it distort the architect's intention. In other words, it should be transparent. The computer possesses the ability to mimic any set of conditions or frame of reference necessary to express a concept. The

*Imagination is more important than knowledge.*

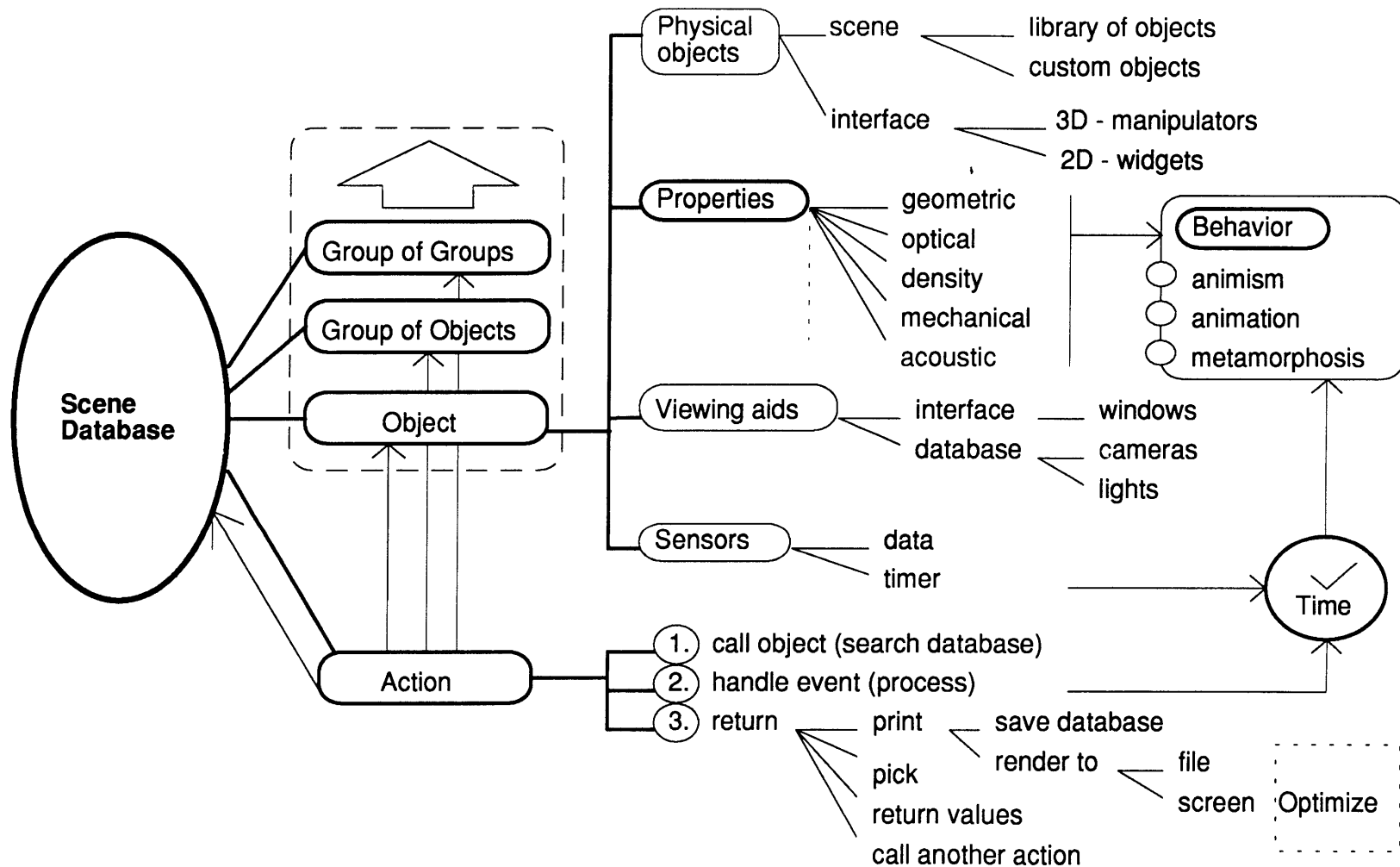


*Albert Einstein*

**digital** medium is the most transparent medium because of its flexible, general attributes.

In the CAD world, **multimedia** has made its most obvious impact by delivering new ways to describe complex projects and then sending them to video for presentation. With the advancements in digital technology, multimedia technology promises to enable interactive presentations, similar to live walkthroughs. The visualization support is obvious. Photo-realistic images and simulated realities are impressive. However, perhaps the most promising area where multimedia can benefit architects, is in helping making decisions in the design process. Otherwise there would be a danger for those images to lose their significance -- they become pretty and shallow, stripped of their content. Representation limited to projected 2D clues often overlook the experience.





## OBJECT ORIENTED 3D TOOLKIT

## **5. Software structure**

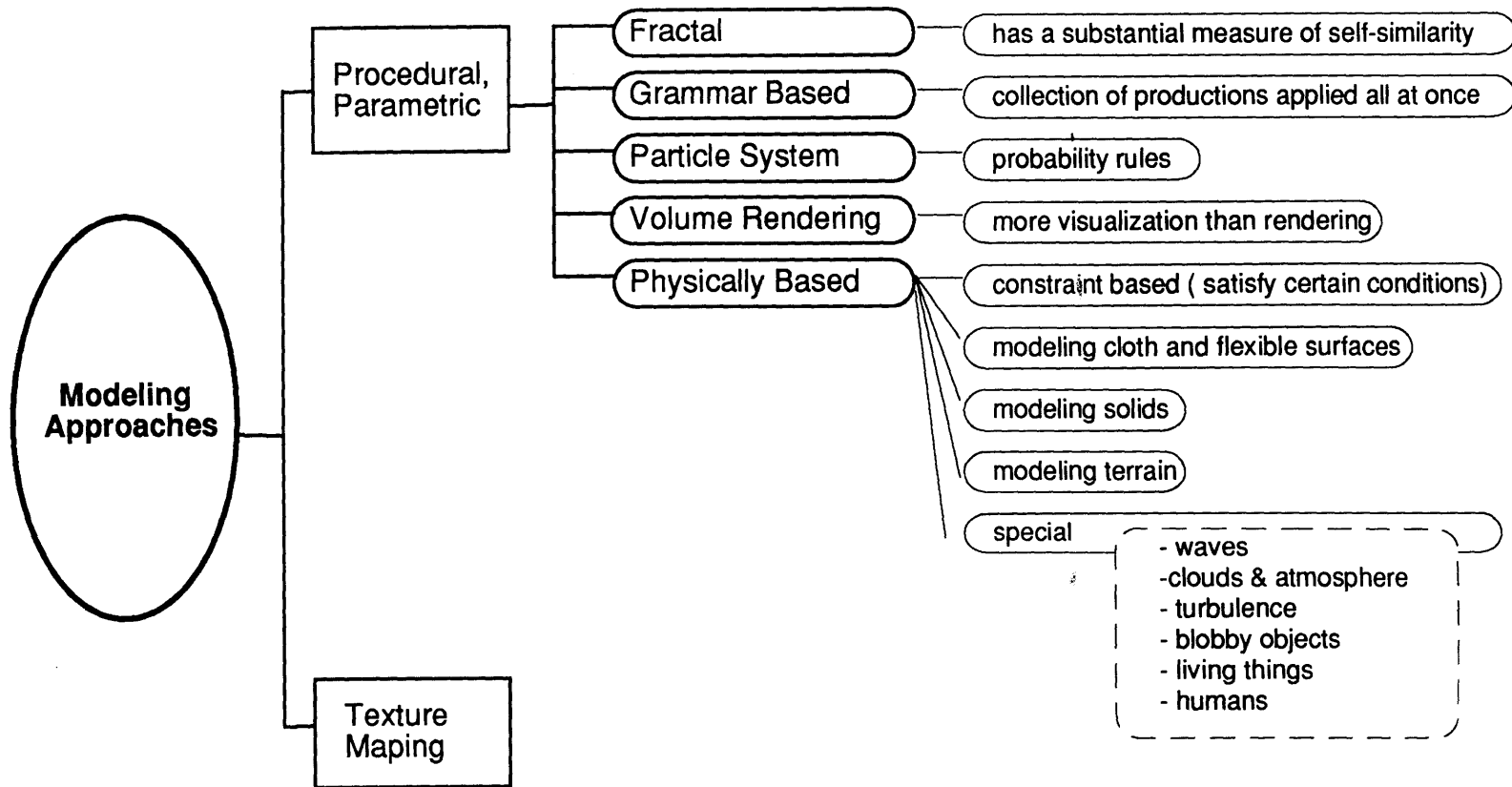


*Toolkit structure for an object oriented 3D database. It represents 3D physical data and operates on it. A similar structure is used in Iris Performer, a programming environment developed by Silicon Graphics Inc.*

The software provides the integration of the experiential storytelling tool. It provides the necessary interface in linking the various peripherals. It also assures the main functionality of the tool by providing three main modules: modeling, manipulation and navigation.

### **5.1. Modeling**

There are several approaches to digital 3D modeling. A concise review is presented in the second edition of "Computer Graphics - principles and practice" [Foley, van Dam, Feiner, Hughes, pg. 1011-1054]. It is important to use an application that optimizes the models for use with a real-time image generation software and hardware. This functionality is achieved on two levels. First, the extensive use of texture mapping that provides photo-realistic representations without the use of elaborate geometric databases. Therefore, advanced modelers like the ones from Alias Research or SoftImage that are based on B-spline surfaces, would be inadequate for the task. Polygon-based modelers like those provided by Wavefront, Software Systems (MultiGen) and Autodesk (AutoCAD) are



## MODELING: ALTERNATIVE APPROACHES

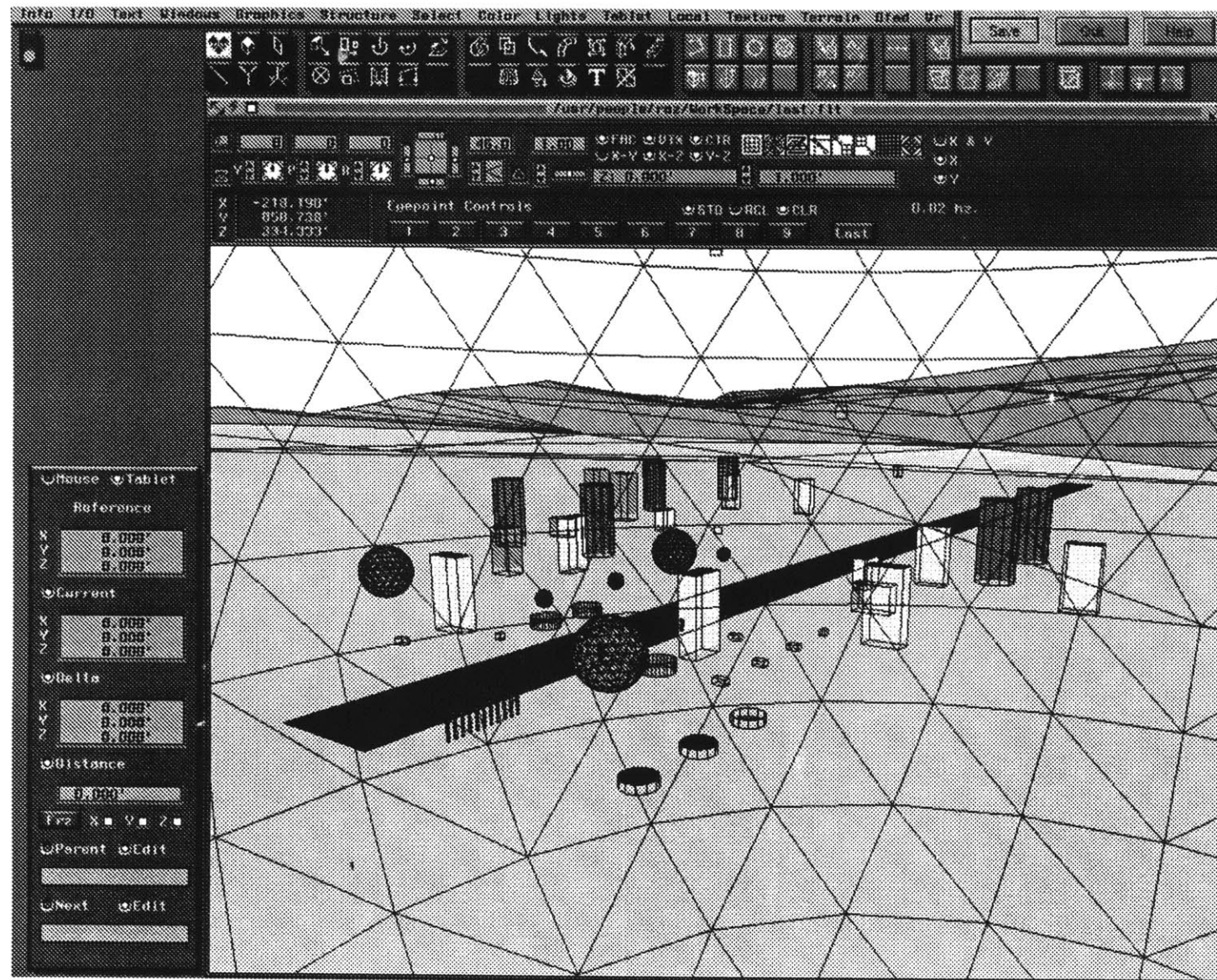
more likely to be suitable for the task. There is a close relationship between the acceptable complexity of the scene description and the graphic capabilities of the hardware. If features described in the model's database cannot be represented through hardware-implemented algorithms, they need to rely on software, which is considerably slower. Flexibility and portability of the models is assured by providing these features to be turned on/off depending on the graphics board available. The second functionality level for optimizing the scene description is assured by providing hierarchical levels of details. This allows each object from the scene to have several geometric representations. This data structure has to be implemented in the file format as it needs to preserve the nesting information for the real-time image generation software. There are several programs that are add-ons to major modeling applications. Among the modeling packages already mentioned and tested within this research, only MultiGen offers this functionality. MultiGen is also specifically tuned to take advantage of specific graphic hardware implementations available on Silicon Graphics workstations. The model developed uses polygonal faces, and a library of scanned images used for texture mapping. Most faces are single sided, with the



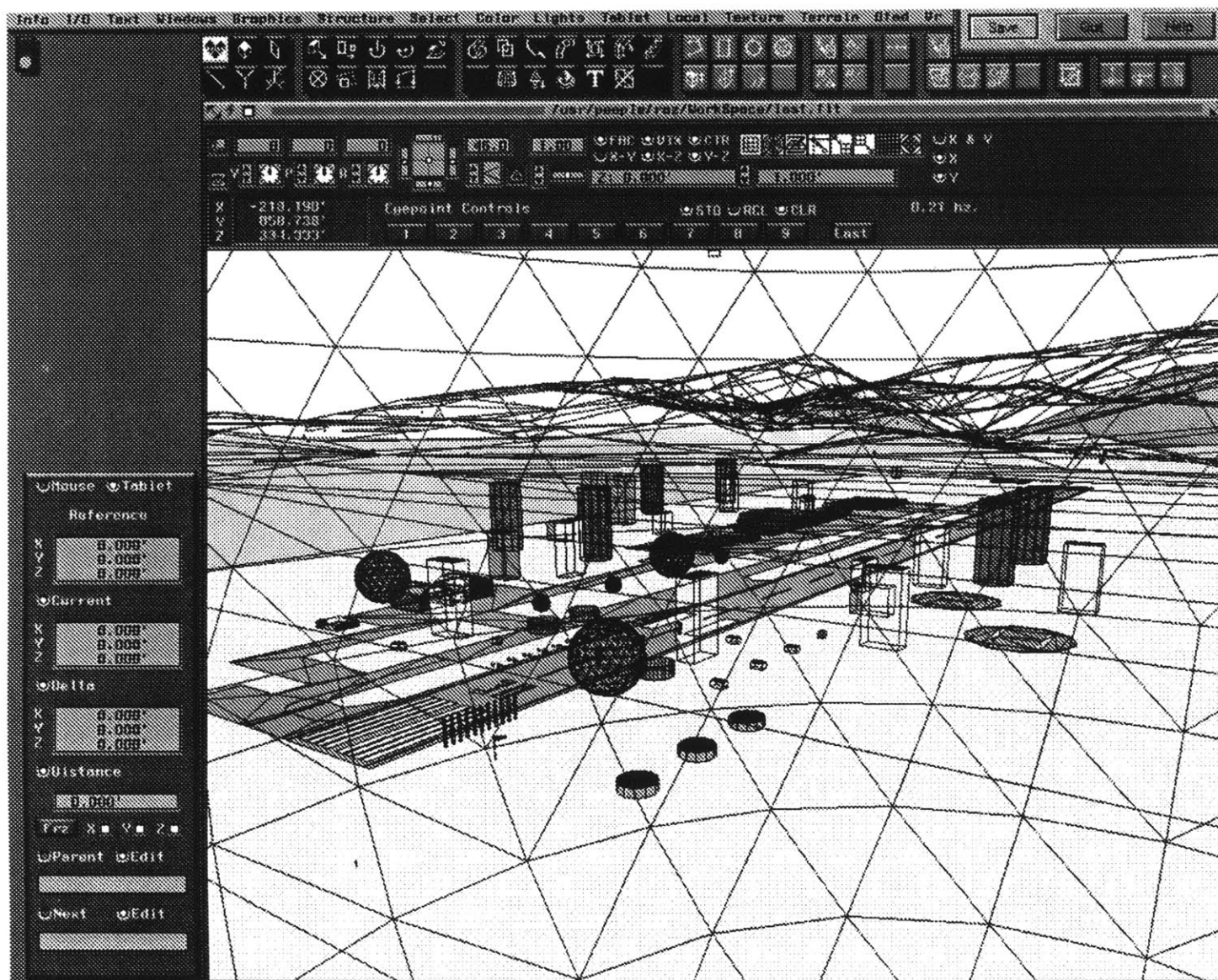


visible side towards the 'exterior'. Exceptions are the faces on 3D objects with transparency maps. Because the backside of these faces is visible, they are double-sided. The applied texture maps require less than 4MB of memory (using the same texture maps in several places or tiling it counts as one).



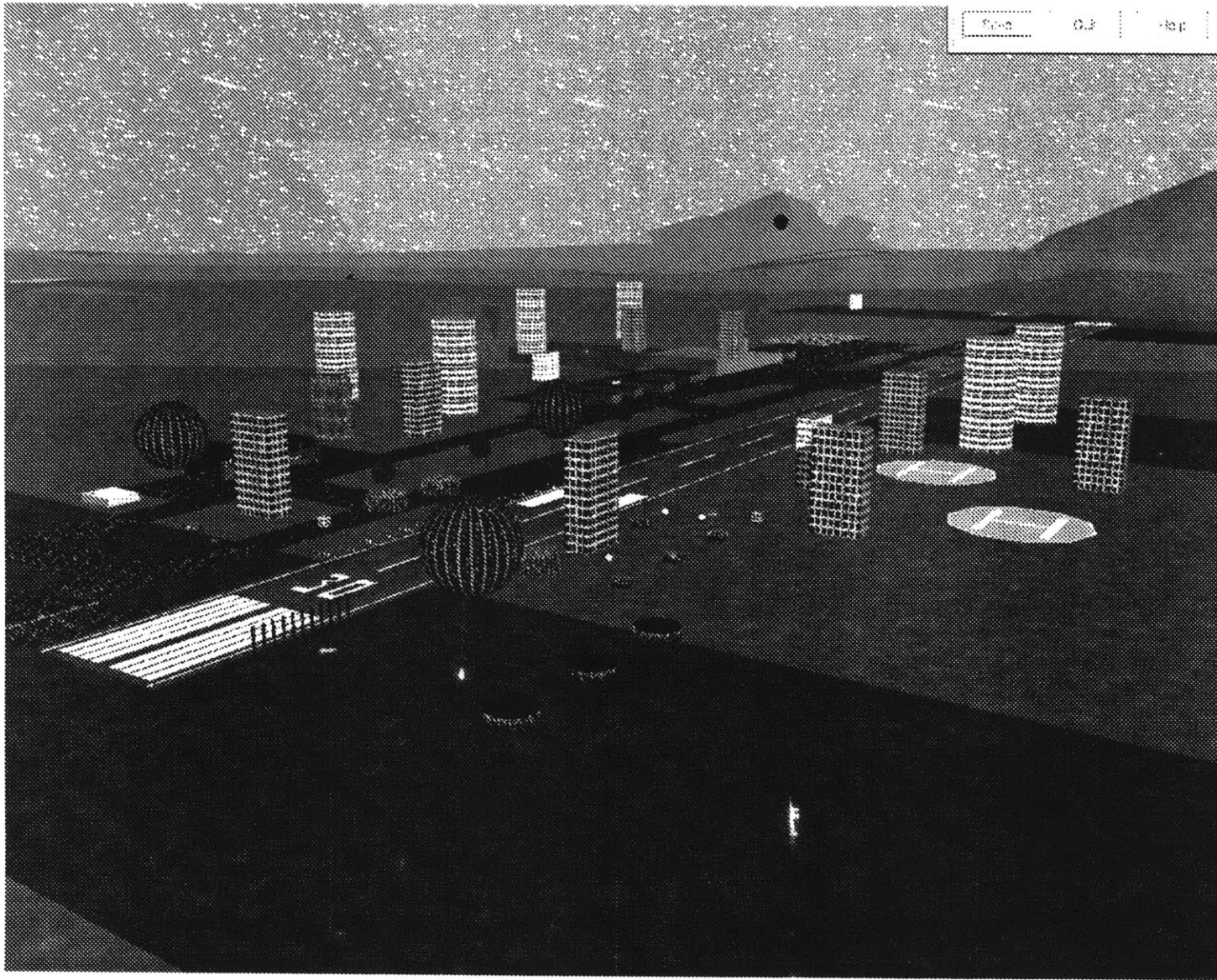






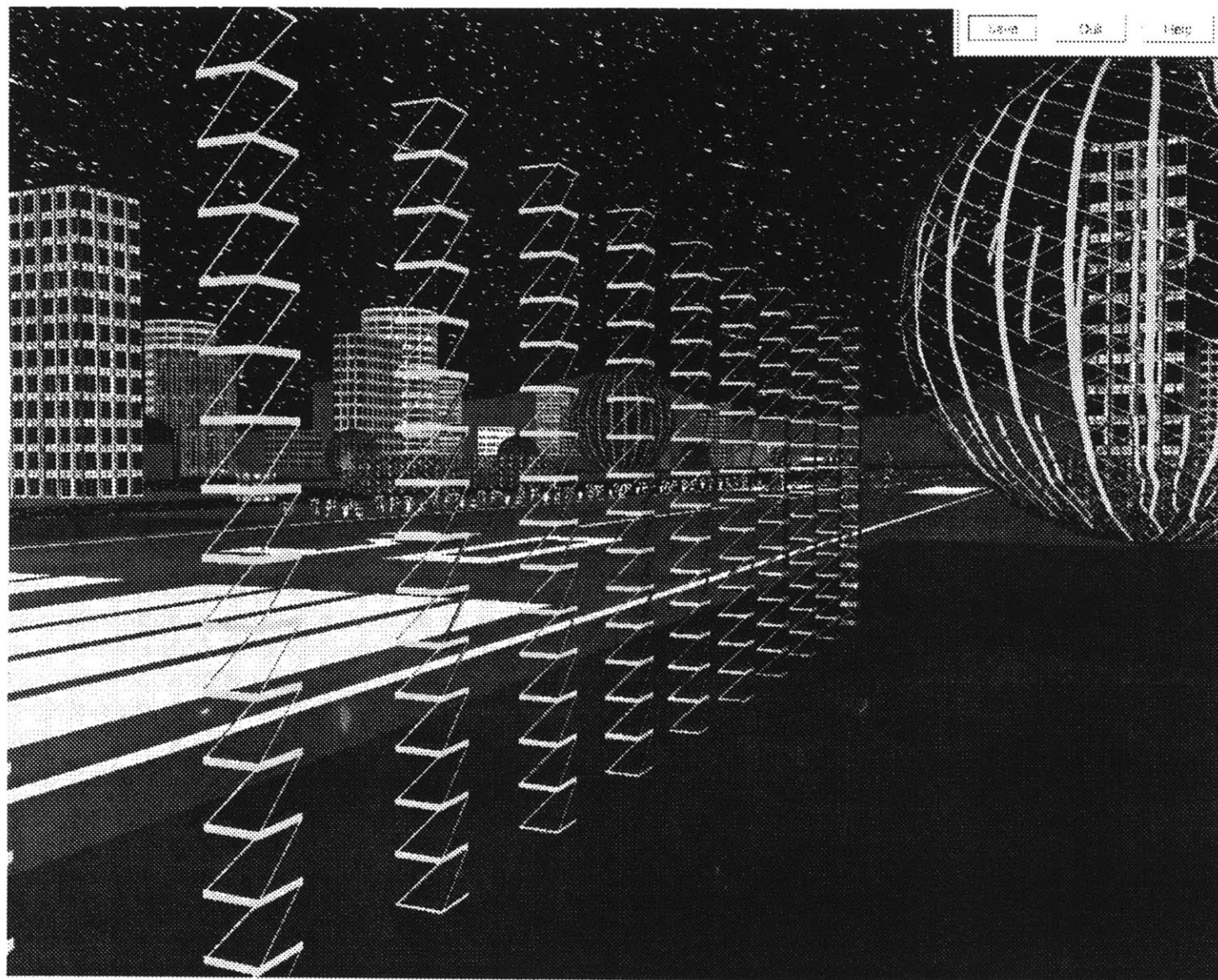




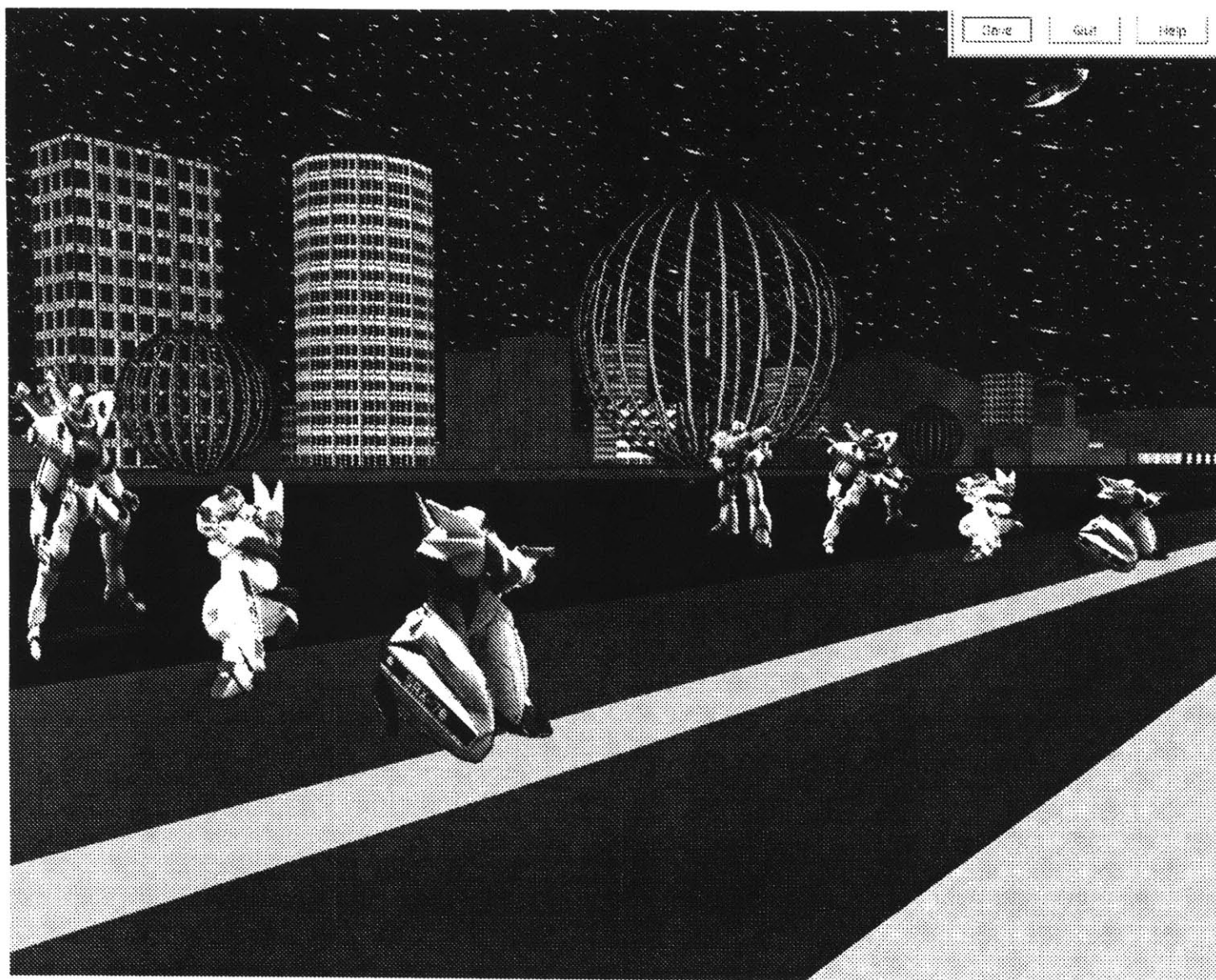




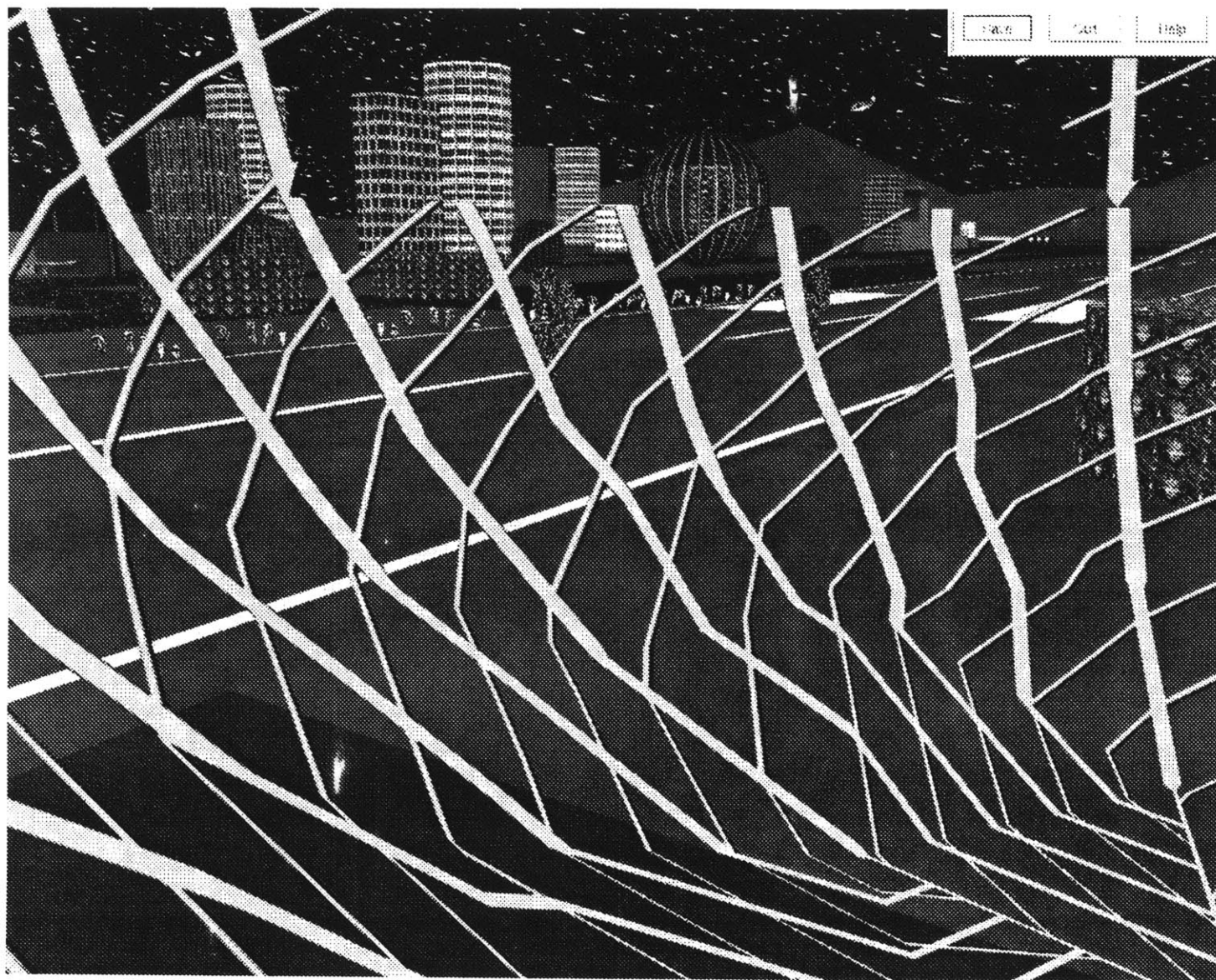






















## **5.2. Positioning**

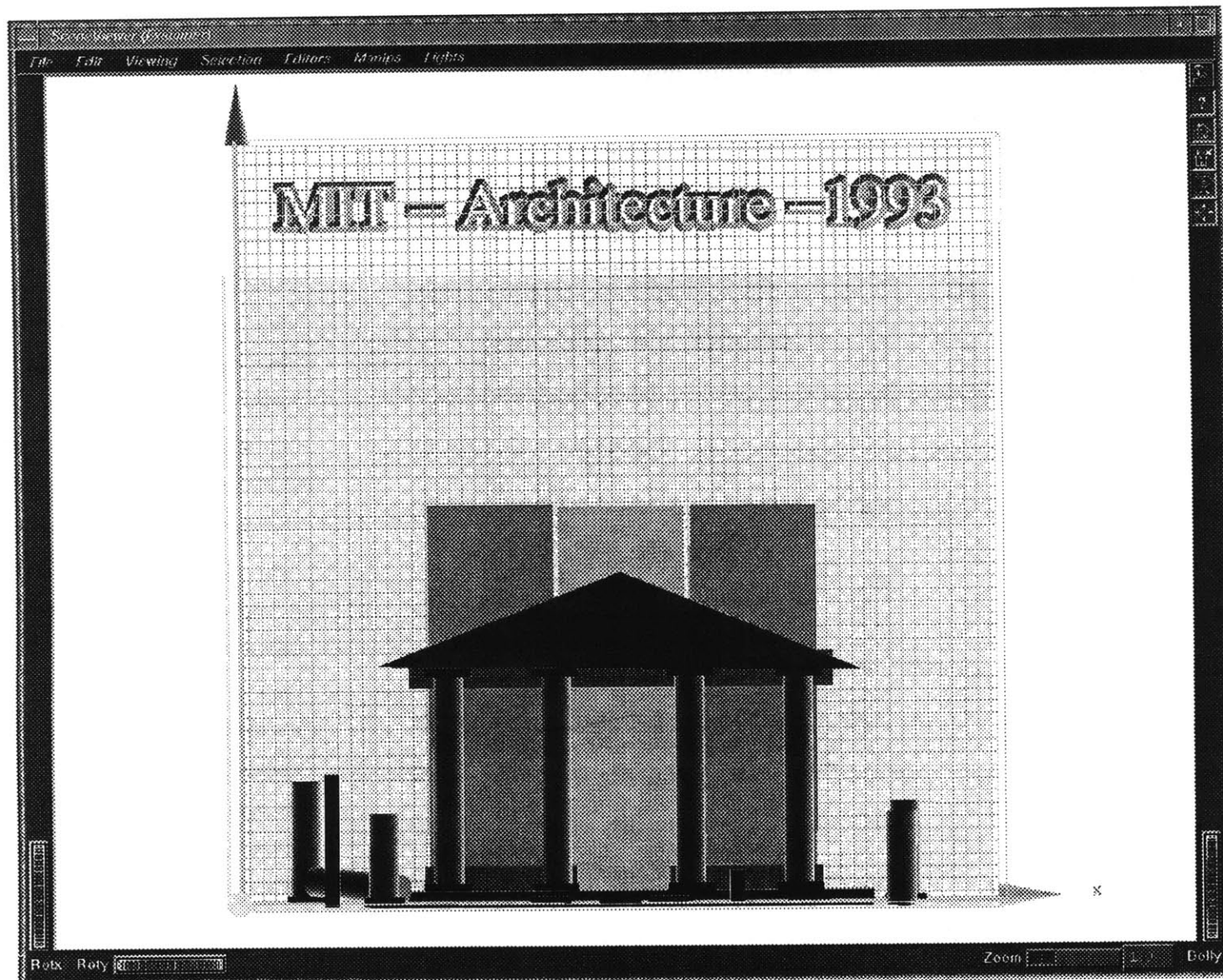
Usually object manipulation is done as an integral part of the modeling or image generation modules. As mentioned previously, traditional digital modeling is constrained by dealing with 2D inputs (mice, digitizers and pens) as well as flat outputs (graphic representations on the two-dimensional surface of a CRT monitor). Compromises have been made to enable input and output at the 3D database level. As part of this research, a positioning method was developed that allows good 3D, spatial referencing without the awkward use of construction planes or rigid viewports. This function was achieved using IrisInventor, a software developer's toolkit provided by Silicon Graphics Inc. When the user selects an object within the scene, the picked object becomes highlighted and a 3D cross-hair is associated to it. The cross-hair is centered on the object and has its orthogonal axis parallel with a relative coordinate system. In the shaded scene with hidden surfaces removed, the user is able to see the location where the cross-hair (reference lines) intersect encountered planes. The intersection of the reference lines with the surrounding objects gives spatial feed-back on the object's position relative to other elements within the scene. Absolute coordinates are

known directly, visually, by the location of where the cross-hair intersects the reference planes. At any point, during the manipulation process, both, relative and absolute, positions of the object are visible and obvious.

Locational determination is visual and with good enough approximation for most compositional purposes. This enables fast and intuitive understanding of spatial understanding of objects represented on a flat medium like a CRT monitor display. Height above ground level and distance between objects becomes readily available information, without the use of awkward commands or nested hierarchical medium. This method provides the information in a more intuitive way since it is closer to our natural perception of space.



*This image, as well as all scenes depicted on page 79 to 95, was generated using the IrisInventor toolkit, developed by Silicon Graphics Inc. The objects were defined directly by code in the Inventor (.inv) file format or by using basic tools available within the toolkit. This view depicts the XZ plane in an almost orthogonal projection. The field of view of the synthetic camera is 1 degree, as it appears next to the zoom slider in the lower, right corner of the frame.*

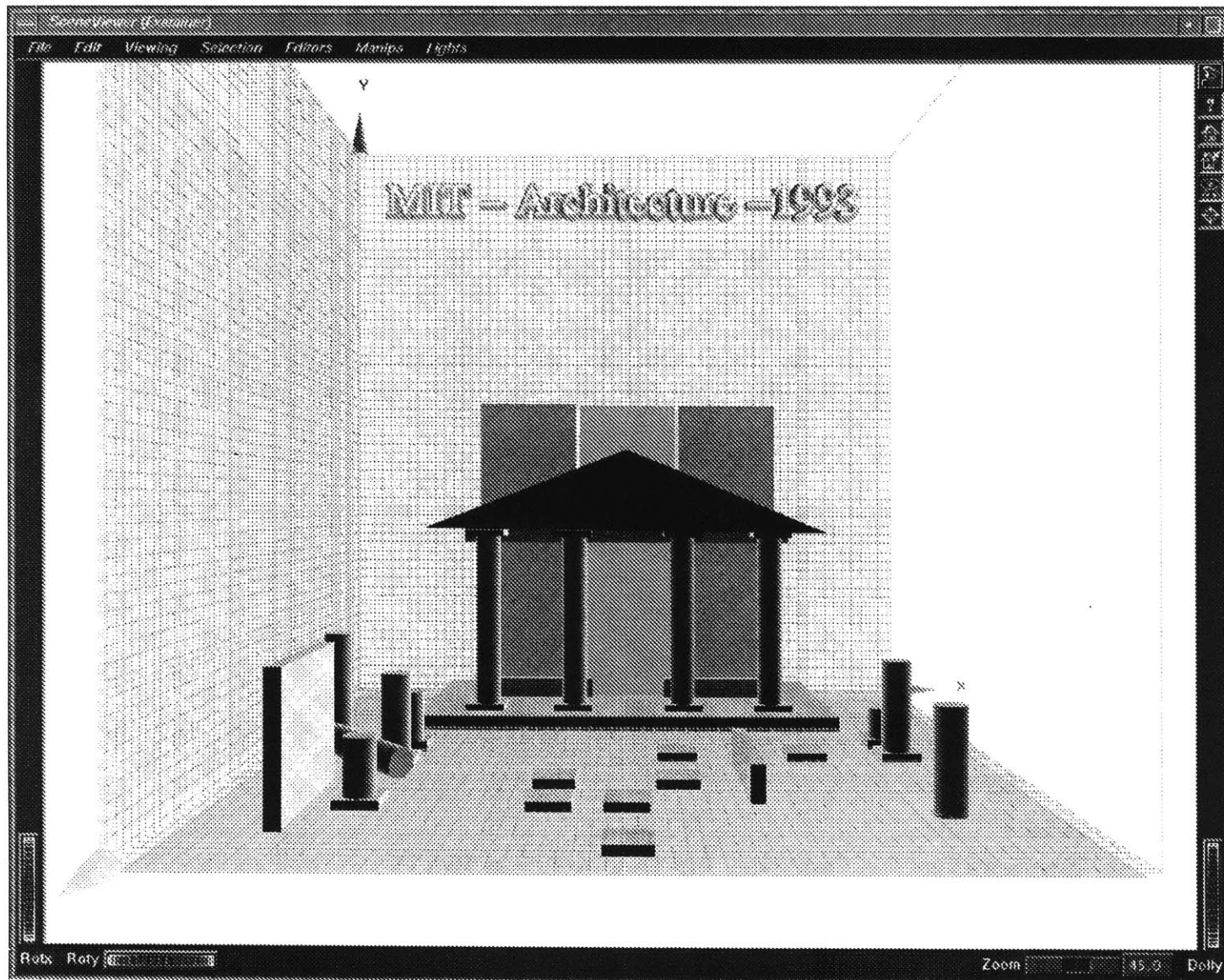


Once localized in space, the object can be translated in space using a 'parallel ruler' concept. Constraints on the axis of translation can be implemented with keyboard commands or, trivial using IrisInventor, with respect to the 2D direction that the input device moves first. This directional cue is understood in 2D by the application and compared with the representation of the scene as it appears on the 2D display. The motion is restricted to an axis or plane, that are intuitively controlled with a two-dimensional input device such as the mouse. Continuous locational feed-back is provided to the user as the cross-hairs are displayed during the whole operation.

The visual feed-back of where the extended cross-hairs intersect the reference planes and surrounding objects provides a better understanding to spatial relationships than was previously possible. This picking and manipulation system provides a faster, more intuitive way of moving objects in 3D space. It addresses the limitations of the visual display. Linked to an input device with six degrees of freedom, this manipulating model provides intuitive input and relevant output.

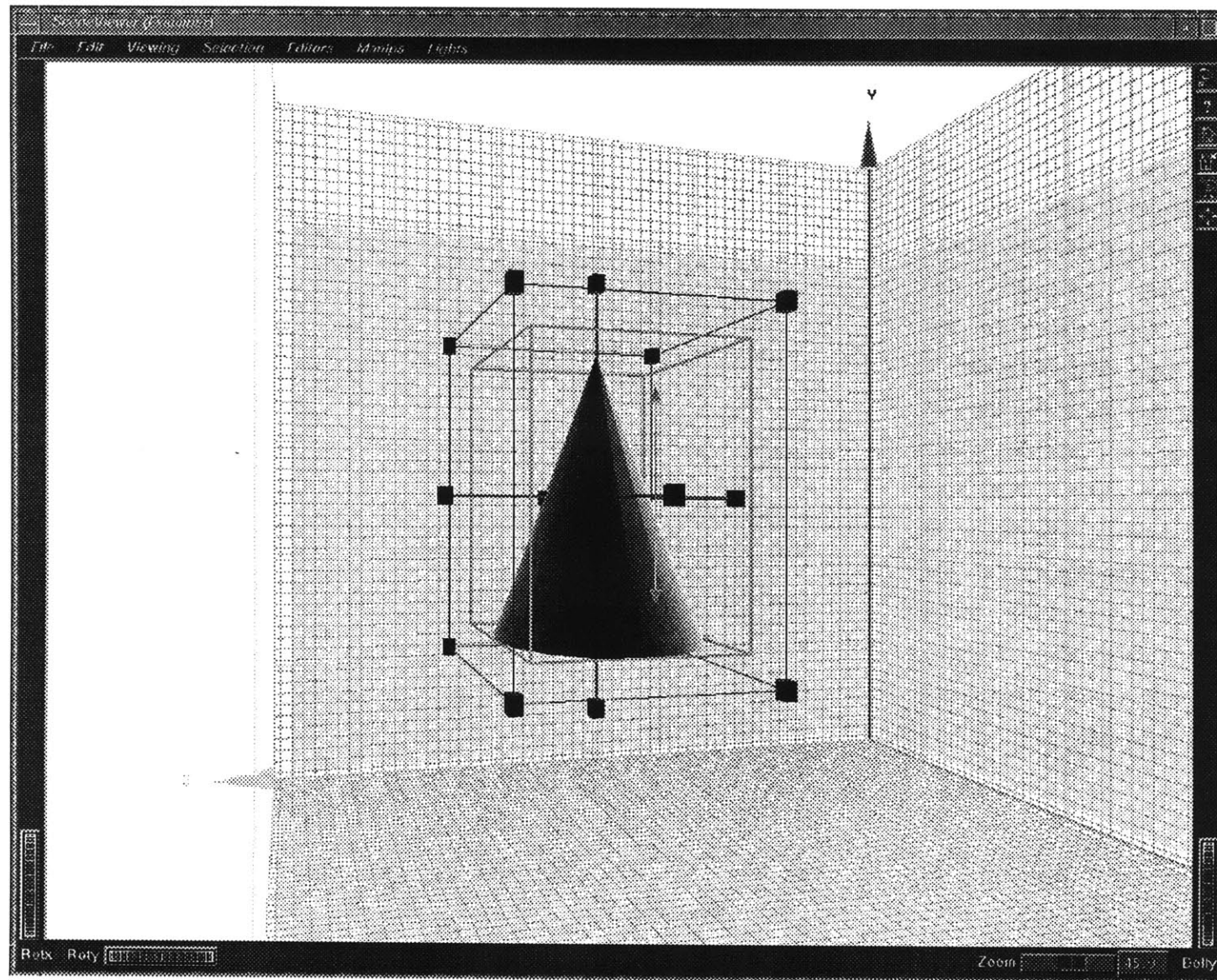


*This image is similar with the view on page 79. In this case, the camera is pointed at the scene under a different angle: 45 degrees. Accordingly, the camera was dollied (translated on the view axis), to get closer to the scene. The camera position was modified in order to assure a relative similar composition. Another effect, determined by those modifications, is the increase in the perception of depth. The perspective is intensified by increasing the field of view (f.o.v.) of the camera lens. Usually 45-46 degrees f.o.v. is used when a close approximation to the human eye is sought. The exact determination depends on the size of the viewed image and the distance from which it is viewed.*





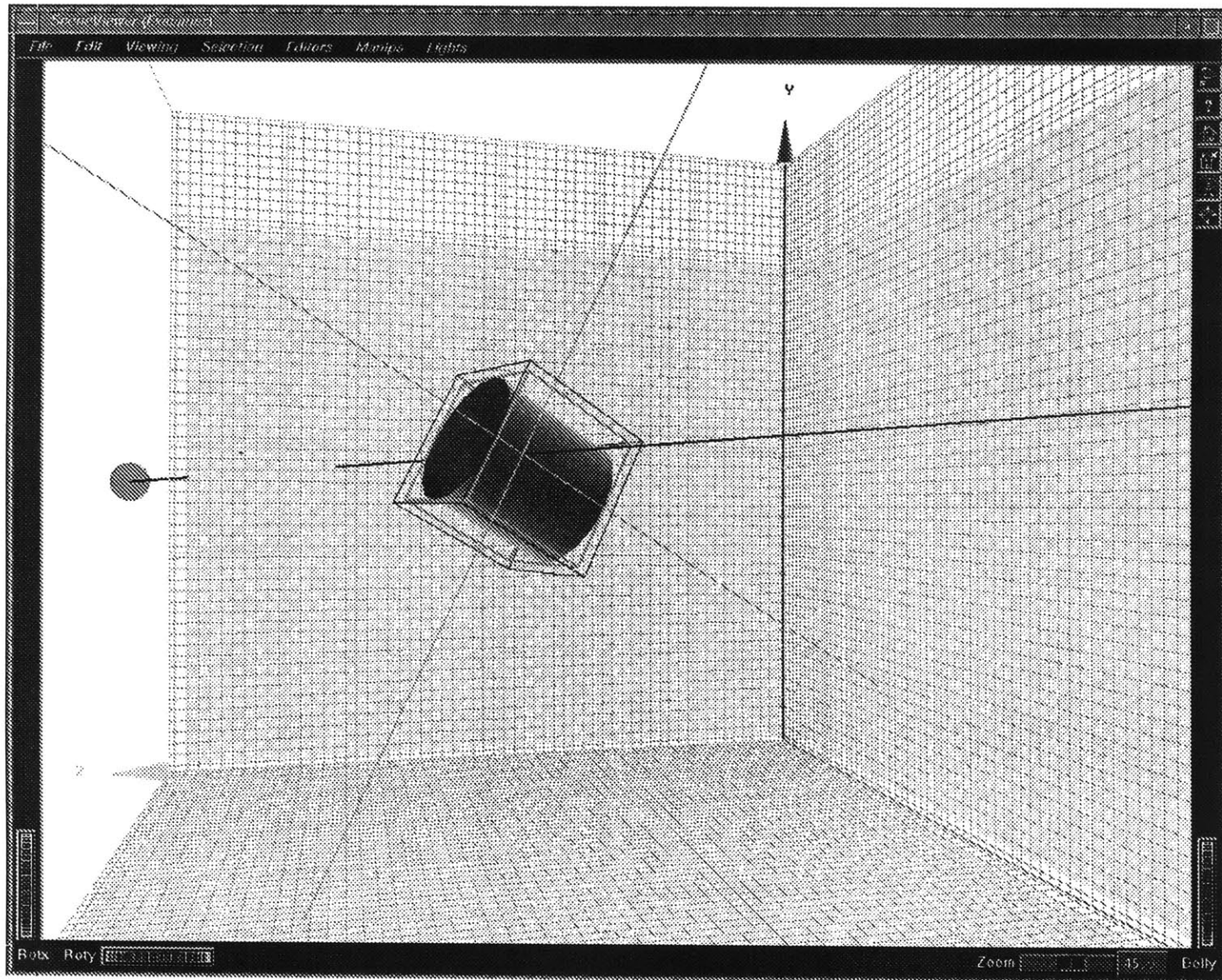
*This image represents a cone in the XYZ orthogonal reference system. A manipulator is associated with the selected cone. This manipulator allows translation alongside any of three orthogonal axis and proportional or non-proportional scaling along those axis. The type of transformation is selected by the user, clicking the mouse over specific regions of the manipulator. The direction is determined by the 2D input device (e.g. mouse). As the user drags the manipulator, the 2D direction of the input is best matched with one of the axis from the flat representation of the camera projection (what is seen on the screen). This way, intuitive eye-hand coordination plays an important role three dimensional manipulation. The amount of translation or scale applied is determined by the translation distance of the input device, in the dragging process.*





*Orthogonal XYZ reference planes have a known dimensional grid. This dimension can be determined by the user to fit a variety of needs. The grid concept is essential to enable a useful referencing system. Manipulators are associated to axis relative to the transformation associated with them. It is important to see the intersection of those relative axis of manipulation with the XYZ reference planes. This way, there is enough visual information to have a good understanding of the object's position and orientation within the scene. The complication of plans, elevations, and other redundant analytical data is avoided.*





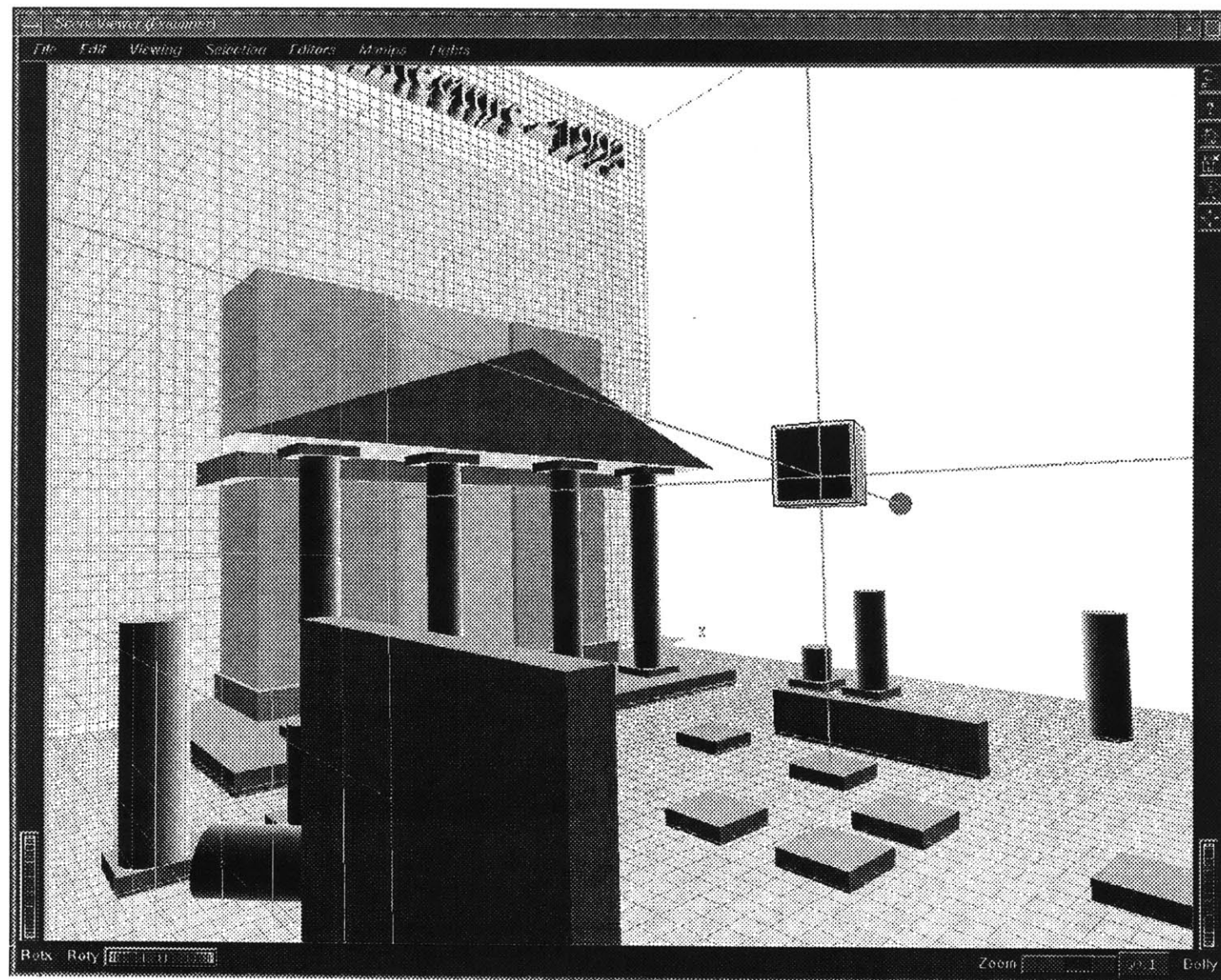


*The same manipulator concept can be adapted for special objects, like cameras and light sources. In this case, the spotlight manipulator has an added functionality. A graphic representation of a cone reveals the light source's field of coverage. This cone can be adjusted to the specific needs of the user. It is useful to enable the proportional scaling of the cone of light, as an intersection with the reference planes or objects in the scene, is most informative.*





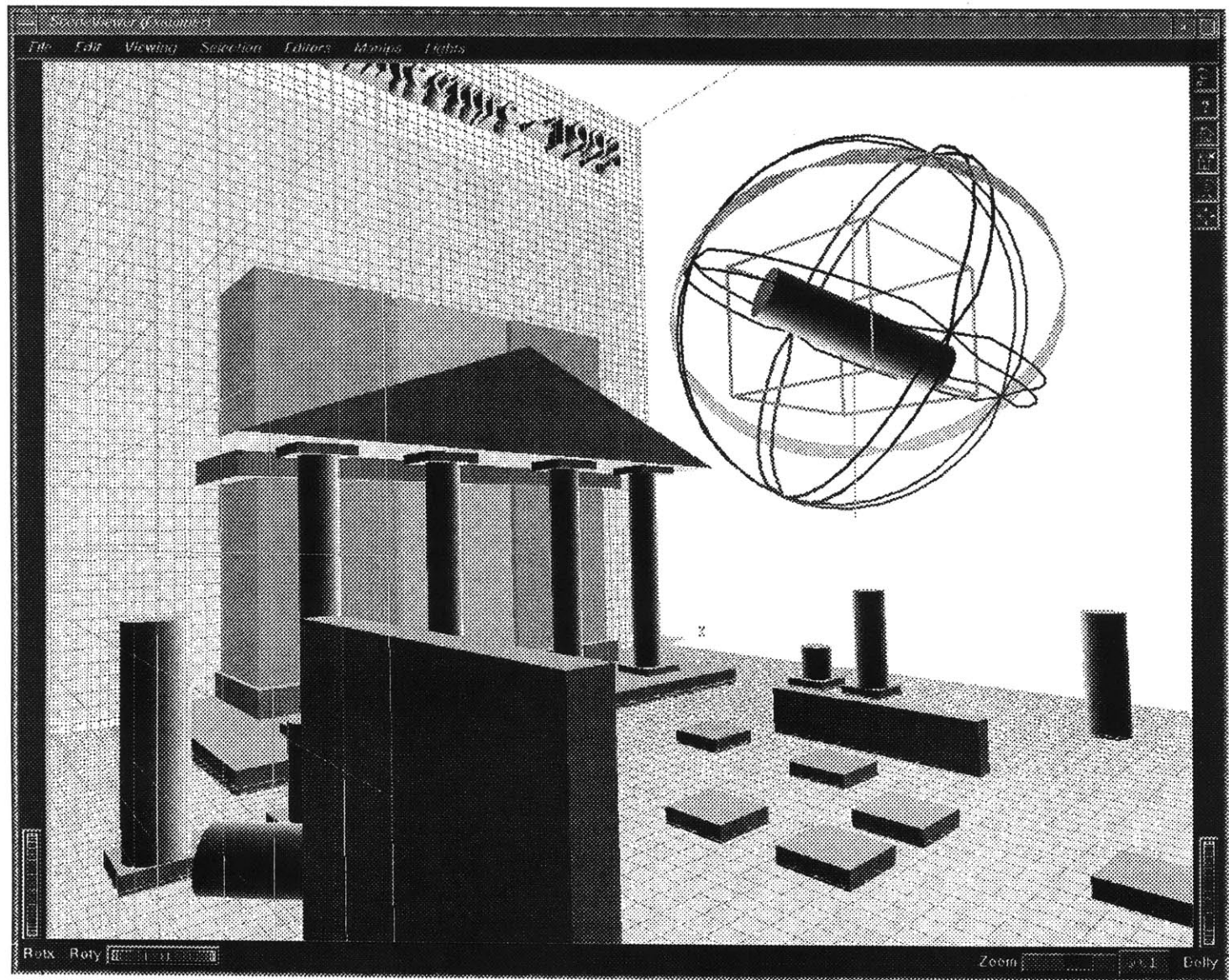
*A cube is positioned in the scene with reference to the objects and the reference grids. The operation can be completed without changing the view or construction planes, and with good. If a high degree of precision is desired, snapping tools can be associated to the manipulator. As in AutoCAD (developed by Autodesk), the manipulator can have a restricted area that centers on adjacent geometric characteristics such as endpoints, midpoints, intersection points, etc.*





*This is an exemplification of a rotational manipulator. Rotation can be controlled on any of the three diameters of the sphere that is represented and that is centered on the object. Additional axis or planes associated with the manipulator and that intersect the reference planes or scene objects, would be very helpful. Additional useful information could be obtained by representing a 'shadow' outline of the object being manipulated. This outline, represented on the XYZ orthogonal planes, would make the transformation even more intuitive.*

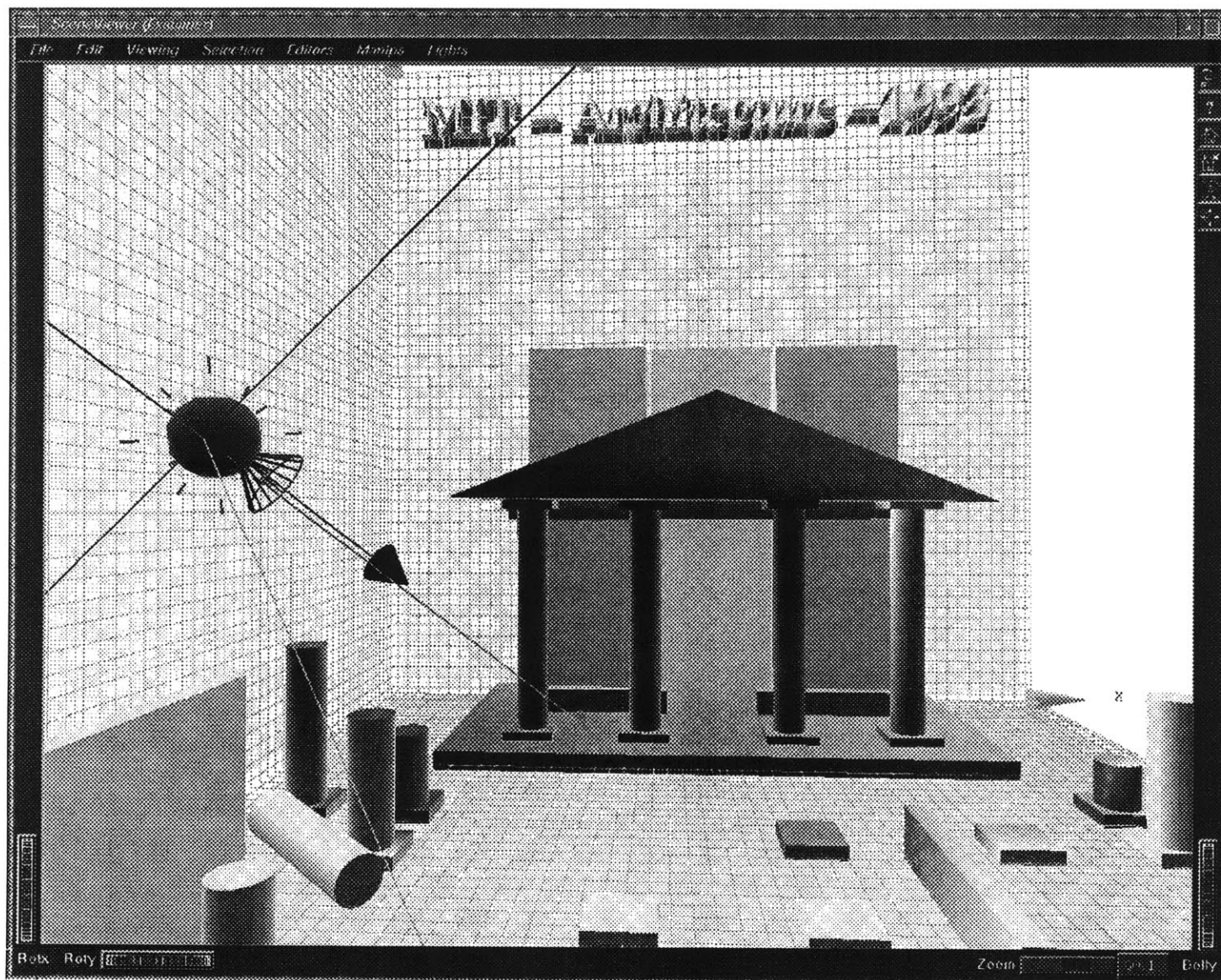






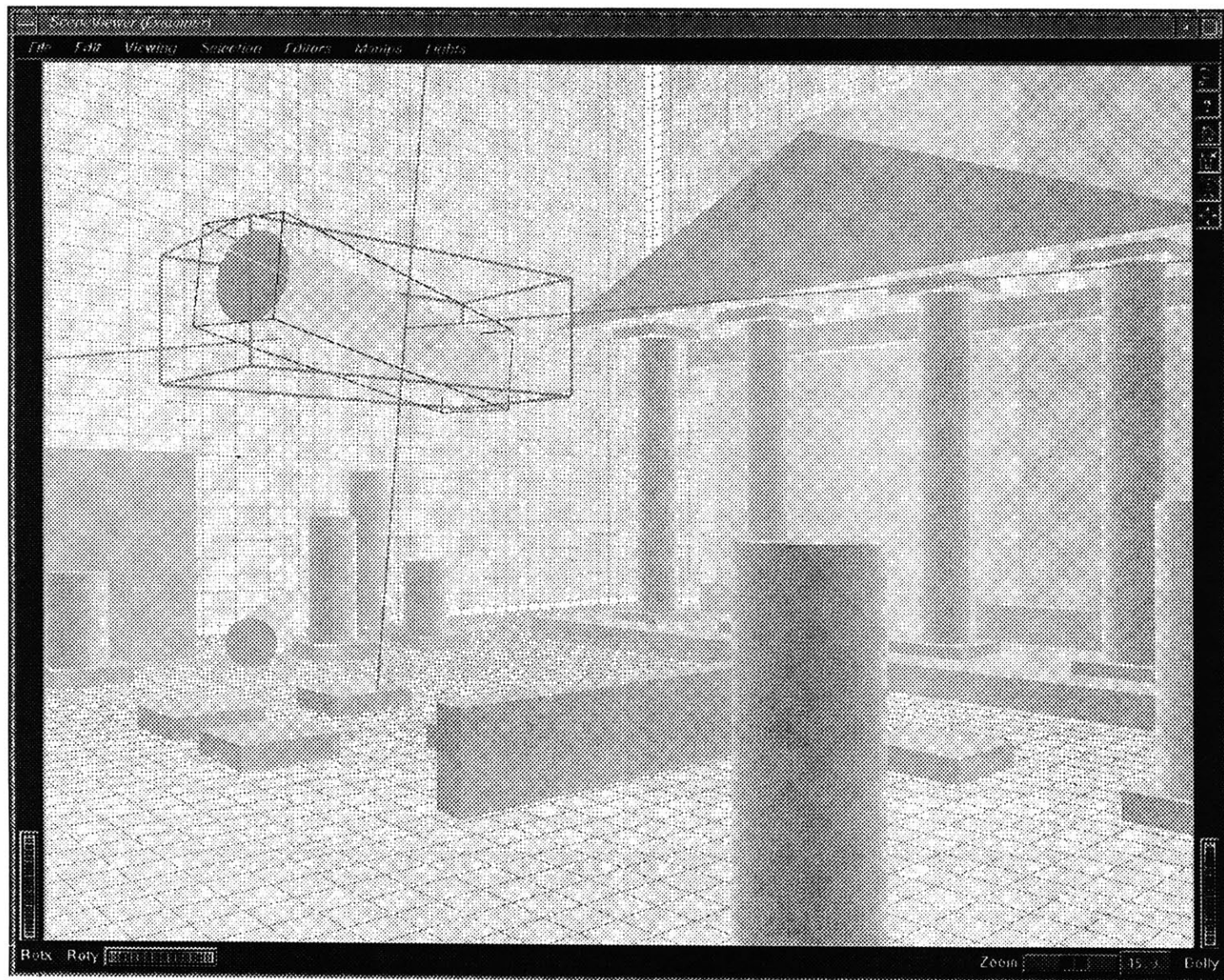
*Example of spotlight placement within the scene. The hardware platform used for this study (Indigo Elan R4000) offers real-time shading with multiple light sources. This is essential for interactive positioning of the spotlight.*







*Chromastereoscopy was used for the generation of enhanced depth cueing. this phenomena is characteristic to human perception and it is due to a symmetrical refraction of the light as it passes through the crystalline. The blue end of the spectrum is refracted towards the exterior of the eyes and the red end towards the interior. Through the process of convergence, the blue objects seem further than the red ones. This explains why, in vivid images like on the CRT monitor, blues seem to recede and reds seem to pop out. This scene is rendered with a blue fog and a red 'headlight' associated to the camera.*





## BIBLIOGRAPHY

- Anderson, Bruce. "Making Sense of Multimedia: Whether Macintosh- or PC-based, systems that meld video, sound, computer graphics, animation and scanned images place formidable demands on the hardware and people that create these complex presentations." *Computer Graphics Review*. - February 1990.
- Aukstakalnis, Steve and David Blatner. *Silicon Mirage: The Art and Science of Virtual Reality*. Edited by Stephen F. Roth. Berkeley, California: Peachpit Press, Inc., 1992. (pages 185-209)
- Arnheim, Rudolf. *Arta si perceptia vizuala: O psihologie a vazului creator*. Translated by Florin Ionescu. Bucharest, Romania: Editura Meridiane, 1979.
- Arnheim, Rudolf. *Film as Art*. Berkeley, California: University of California Press, 1957.
- Benedikt, Michael, editor. *Cyberspace: First Steps*. Cambridge, Massachusetts: The MIT Press, 1992. (pages 133-208, 427-428.)
- Biggs, Dan. "Simulating and Animating Project Designs: DDS uses a variety of tools and techniques." *Cadence*. June 1990.
- Billups, Scott. "Think Integration: It's the Future Of Animation, DTV: More Mac." *AV Video*. July 1991.
- Blake, Randolph and Robert Sekular. *Perception*. New York: Alfred A. Knopf, 1985.
- Boesjes, Eimar M. "Built-In Rendering: Rendering from the start eliminates repetition." *Cadence*. April 1991.
- Bosjes, Elimar. "A Rendering Revolution: The need for integrating rendering in autocad applications."
- Branscomb, Hill. "Following the Yellow-Brick Road: Virtual Reality takes entertainment into the next century." *Vizons* - Fall 1991.

- Bruner, Jerome. Part One: Two Natural Kinds Actual Minds, Possible Worlds On Narratives. Cambridge, Massachusetts: Harvard University Press, 1986.
- Buday, Richard. "Architecture and Imagery." CADalyst - March 1992.
- Burch, Noel. Theory of Film Practice. Princeton, New Jersey: Princeton University Press, 1969.
- Casper, Patricia A. and Kantowitz, Barry H. Seeing Tones and Hearing Rectangles: Attending to Simultaneous Auditory and Visual Events. Department of Psychological Sciences Purdue University, Indiana 1985.
- Ching, Francis D.K., Architecture Form Space & Order. New York: Van Nostrand Reinhold Co., 1979.
- Coates, Del. "Daemonic CAD: The practical implementation of AI."
- Coates, Del. "Physically Base Modeling: Eye to the Future: focus: shading/rendering." MicroCAD News. March 1990.
- Coates, Del. "Redesigning Design." MCN - November 1991.
- Cooper, Muriel. "Words, Images, Tools, and Ideas." Plan Number 11: Perspective on Two Decades School of Architecture and Planning. Massachusetts Institute of Technology (1980), pg 105.
- Deleuze, Gilles. Cinema 1: The Movement-Image. The Athlone Press, London - 1983.
- Elton, Martin C. J. The Spoken and the Printed Word in Electronic Communications. Electronic Publishing Plus.
- Enache, Mircea and Iulius Ionescu. Geometrie Descriptiva si Perspectiva. Bucuresti, Romania: Editura Didactica si Pedagogica, 1983.
- Evans, Dale E. "Issues in Imaging: Image processing and rendering." Cadence. July 1991.
- Evans, Dale E. "Pretty Pictures of Playback: Shading and rendering - who needs it ?." Cadence. July 1990.

Fleisher, Aaron. Grammatical Architecture? School of Architecture and Planning. Massachusetts Institute of Technology, Cambridge 1991.

Foley, James D. and van Dam, Andries and Feiner, Steven K. and Hughes, John F. Addison-Wesley Publishing Company, Inc. - 1990

Forcade, Tim. "Campus Cut Ups." Cadence. July 1991.

Forcade, Tim. "Presenting Multimedia: Why 3D Modeling and Rendering?" Cadence. April 1991.

Forcade, Tim. "Real-World Rendering." MCN. October 1991.

Gatta, Kevin and Lange, Gusty and Lyons, Marilyn Foundations of Graphic Design.

Gerstner, Karl. Designing Programmes. Switzerland Arthur Niggli Ltd, Teufen AR, 1968.

Hendrix, Gary. "An Object Oriented Intro." Symantec - Winter 1992.

Honor, Richard. "Graphics Aided Design: Visualize a project." Cadence. July 1990.

Johnson, Patricia. Electronic Photos, Graphic Arts, and the Imaging Learning. Curve Advanced Imaging, 1992.

Haase, Bruce. "A Place for Shading and Rendering." MicroCAD News. March 1990.

Haber, Lynn. "Sight For The Masses" DEC Professional. July 1991.

Hiss, Tony. The Experience of Place: A New Way of Looking at and Dealing with our Radically Changing Cities and Countryside. New York: Vintage Books, 1990.

Harrell, Jean Gabbert. "Chapter Two: A case for Edmund Gurney." Soundtracks. Prometheus Books 1986.

Hochberg, Julian and Virginia Brooks. The Perception of Motion Pictures: Handbook of Perception, Vol. X. Academic Press, Inc. 1978.

Ionesco, Eugene. The Bald Soprano

- Iris Partner Catalog: A Comprehensive Resource Guide to Silicon Graphics Third-Party Software Applications, Peripherals and Services. Silicon Graphics: Computer Systems, Fall 1992.
- Isenhour, John Preston. "The Effects of Context and Order in Film Editing." AVCR. Vol 23 no.1 Spring 1975.
- Itten, Johannes. The Art of Color. New York: Van Nostrand Reinhold Company
- Jadrnicek, Rik. "Bring a Project to Life with Animation: Creating dynamic client presentations." Cadence. June 1990.
- Jadrnicek, Rik and Sarath, Patrice. "Creating a Presentation: Competition impels architect toward rendering and animation."
- Kelley, Al and Ira Pohl. A Book on C: Programming in C. Edited by Allan Apt. Redwood City, California: The Benjamin/ Cummings Publishing Company, Inc., 1990.
- Kepes, Gyorgy. Language of Vision: Painting, Photography, Advertising-Design. Paul Theobald and Company, 1961.
- Klee, Paul. Pedagogical Sketchbook. New York: Frederick A. Praeger 1953.
- Krier, Rob. Elements of Architecture. Edited by Dr. Andreas Papdakis. Architectural Design Profile: Volume 53. London: AD Publications, 1983.
- Lang, Laura. "Creating 3-D Realities With CAD." Design Management. - November 1991.
- Lavroff, Nicholas. Virtual Reality Playhouse. Corte Madera, California: Waite Group Press, 1992.
- Neagu, Razvan. "Computer Anaglyphography: The stereographic Sketch Tool." The Media Lab, Massachusetts Institute of Technology 1991.
- Negroponce, Nicholas. "Arts and Media Technology." Plan Number 11: Perspective on Two Decades School of Architecture and Planning. Massachusetts Institute of Technology (1980), pg 19.



- Negroponte, Nicholas. "Machine Dreams." Technology Review - January 1992.
- Novak, Marcos. "Liquid Architecture in Cyberspace." Cyberspace: First Steps. Edited by Michael Benedikt. Cambridge, Massachusetts: The MIT Press, 1992, pages 225-254.
- MacNicol, Gregory. "Image Processing: the Basics"
- McCullough, Malcolm. "Computer Aided Conceptual Design? A contradiction in terms?" Cadence. July 1990.
- Mallary, Robert. Schema of Art and Design
- Mast, Gerald. (Recorded) Sound: Film, Cinema, Movie
- Mc Cullough, Malcolm. "The Design Network: The Graduate School of Design at Harvard University." MicroCAD News. June 1989.
- McManus ,Maureen. "The Message of Multimedia: Multisensory Approach to the Dynamic Document of the 1990's." MCN. April 1991.
- Miller, F. D. "3-D Animation Within GRASP for Supre VGA: PC Plus." AV Video. July 1991.
- Meyer, Ann. "3D Modeling Techniques: Part one: Software evolving slowly from 2D beginings." MCN. June1991.
- Minsky, Martin. The Society of Mind. New York: Simon & Schuster, Inc., 1985.
- Mitchell, William J. and Malcolm McCullough. Digital Design Media: A Handbook for Architects and Design Professionals. New York: Van Nostrand Reinhold, 1991.
- Mitchell, William J. The Logic of Architecture: Design, Computation, and Cognition. Cambridge, Massachusetts: The M.I.T. Press, 1990.
- Mitchell W. J. and Stiny, G. "The Palladian Grammar" Environment and Planning B, 1978, volume 5, pages 5-18
- Moholy-Nagy, Laszlo. Painting Photography Film. Cambridge, Massachusetts MIT Press, 1973.

O'Connell, Brian. "Media Integration Though still in its infancy and searching for definition, multimedia will represent a key integration technology for the 1990s." DEC Professional. July 1991.

Oliverio, Barbara. "The ABCs, RGBs, and CMYs of Color Image Processing." MicroCAD News. March 1990.

O'Malley, Michael. "High-Res Imaging and Animation." Cadence. April 1989.

Piantanida, Tom and Boman, K. Duane and Gille, Jennifer "Human Perceptual Issues and Virtual Reality" - Virtual Reality Systems vol1 no1 - New York 1993

Pietra, Chuck. "Paving the Way for the Olympics: An architectural firm's first venture into animation." CADalyst. January 1992.

Pimentel, Ken and Kevin Teixeira. Virtual Reality: Through the Looking Glass. New York: Intel/ Windcrest/ McGraw - Hill, Inc., 1993.

#### The Principles of Animation

Proffitt, Dennis R. and Kaiser, Mary K. Perceiving environmental properties from motion information: minimal conditions: Pictorial Communication in Virtual and Real Environments. London, Taylor & Francis, 1991.

Prueitt, Melvin L. Art and the Computer. McGraw-Hill, Inc. 1984.

Rasmussen, Steen Eiler. Experiencing Architecture. Cambridge, Massachusetts: The M.I.T. Press, 1959.

Randall, Randy. "Directing the Art: Realizing the possibilities of computer animation."

Randall, Randy. "From the Stars Down to Earth: Realism is in the details." Cadence. April 1991.

Randall, Randy. "Is It Real or Is It Animation? Realism in Computer Graphics Presentations." Cadence. February 1991.

Randall, Randy. "What is Rendering?" Cadence. July 1990.

- Rheingold, Howard. "Virtual Reality: Is It Real Yet?" Publish. August 1991.
- Rheingold, Howard. "Visual, Intelligent, and Personal." Publish. March 1991.
- Reed, Alan. "Computer Rendering Put In Proper Context." Cadence. June 1989.
- Reisz, Karel and Millar, Gavin. "The Technique of Film Editing:" Editing the Picture. Boston, Massachusetts: Focal Press, 1978.
- Rodriguez, Walter. "The Art of Design Steps to realizing bright ideas: Design Methodology." MCN - March 1991.
- Roberts, Andrew F. "Challenges Found in Change: Parametric Design Flexibility Answers With What-If Analyses." MCN. June 1991.
- Sekuler, Robert and Randolph Blake. Perception. Alfred A. Knopf, Inc. 1985.
- Shostak, Seth. "The Ultimate Motion Imaging System: What-and When?" Advanced Imaging. August 1992, Pages 39-43, 58.
- Silverstone, Stuart. "Personal Media: A conversation with Nicholas Negroponte." Aldus Magazine. - January/February 1992.
- Smith, Cecil. "The Resolution Solution." AV Video - November 1991.
- Smith, Thomas G. Aguiere. "Stratification:" Toward a Computer Representation of the Moving Image. The Media Lab, Massachusetts Institute of Technology 1991.
- Sturman, David J. "Motion Picture Cameras and Computer Graphics." The Media Lab, Massachusetts Institute of Technology 1989.
- Szarkowski, John. The Photographer's Eye. The Museum of Modern Art 1966.
- Thiis-Evensen, Thomas Archetypes in Architecture Norwegian University Press 1987.
- Thalmann, Daniel, editor. Scientific Visualization and Graphics Simulation. Chichester, England: John Wiley & Sons, 1990.
- Wachman, Joel "Synthetic Cameras / Real motion" Camera Dynamics in a Simulated World. The Media Lab, Massachusetts Institute of Technology 1989.

Wertheimer, Max "Principles of perceptual organization" Readings in perception  
Princeton, N.J.: Van Nostrand.

Wexelblat, Alan. "Giving Meaning to Place: Semantic Spaces." Cyperspace: First  
Steps. Edited by Michael Benedikt. Cambridge, Massachusetts: The MIT Press,  
1992, pages 255-271.

Young, Kim H. "The Right Stuff: The finer points of a 'User-Friendly' CAD system."  
MCN - June 1991.

## PHOTO CREDITS

Images Used as texture maps in the Multigen model

Giger, H.R. Giger's Alien. Edited by Mia Bonzanigo. Translated by Hugh Young.  
Beverly Hills California: Morpheus International, 1989. page 3, 15, 59, 61

Orgun Link World: Super 3D Show/ Air Combat! Hobby Japan. April 1992 No. 275 Vol  
4. page 8, 14, 16, 73.

Parallel Lines: The Science Fiction Illustrations of Peter Elson and Chris Moore. New  
York: A Dragon's Dream Book, 1981. Page 21, 23.

Rowan-Robinson, Michael. Our Universe: An Armchair Guide. New York:  
W.H.Freeman and Company, 1990. Page 125

Diehl, Gaston. Vasarely. New York: Crown Publishers, 1991. Page 69, 71, 87